



ENEPES

**an Effective Surface Finish for
Enhancing Electromigration
Reliability in Solder Joints**





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Abstract— With the continued miniaturization and performance enhancement of electronic devices, electromigration (EM) has become a critical reliability concern in solder joints. To enhance electromigration (EM) reliability, alternative solder joint surface finish technologies are needed to replace conventional electroless nickel/immersion gold (ENIG) and electroless nickel/electroless palladium/immersion gold (ENEPIG). In this study, electroless nickel / electroless palladium / electroless silver (ENEPES) with Ag thicknesses of 0.05 μm and 0.2 μm was investigated as a potential alternative. EM tests were conducted at 150 °C under a current density of 14 kA/cm², and the mean time to failure (MTTF) was evaluated. The results showed that ENEPES exhibited superior EM reliability compared with ENEPIG. The MTTF increased by 22.5% and 75.4% for Ag thicknesses of 0.05 μm and 0.2 μm , respectively, relative to ENEPIG. Microstructural analyses using field-emission scanning electron microscopy (FE-SEM) and energy-dispersive X-ray spectroscopy (EDS) revealed that the improved EM reliability of ENEPES is attributed to the localized formation of a thin Ag₃Sn layer at the surface finish/solder interface. This layer effectively suppresses intermetallic compounds (IMCs) growth and diffusion under EM stressing.

Keywords— *electromigration, reliability, microstructure, IMC, electroless silver plating*

I. INTRODUCTION

In recent years, the rapid development of advanced technologies such as artificial intelligence (AI) has driven the miniaturization and performance enhancement of electronic devices, particularly those used in high-performance computing (HPC). As a result, electronic components increasingly require high-density packaging, which leads to higher current densities being applied to solder joints in integrated circuits (ICs). Under such conditions, electromigration (EM), in which metal atoms diffuse under the momentum transfer from electrons (electron wind force), occurs. During EM stressing, metal atoms diffuse from the cathode side to the anode side. This process results in void formation and growth at the cathode side. These EM-induced voids increase the electrical resistance of solder joints and may ultimately lead to open circuits [1]. Therefore, EM is one of the most critical reliability challenges in high-current and high-power electronic packaging. There are two main approaches to improve EM reliability. The first is to reduce the current density applied to solder joints [2]. The second focuses on enhancing the performance of the solder joints through

materials and interfacial engineering. In particular, the solder alloy composition, microstructure, and intermetallic compounds (IMCs) formed at the surface finish/solder interface have been shown to strongly influence EM behavior. Consequently, extensive research efforts have been devoted to improve EM reliability through material-level approaches [3–10].

Conventional surface finishes, such as electroless nickel / immersion gold (ENIG) and electroless nickel / electroless palladium / immersion gold (ENEPIG), have been widely adopted for solder joints due to their excellent corrosion resistance, electrical conductivity, and solder joint reliability (SJR). However, under high current densities, these Au-based surface finishes are prone to EM degradation. Moreover, the recent surge in gold prices has significantly increased manufacturing costs, creating strong demand for reducing Au usage or alternative surface finish technologies.

Ag is well known for its high electrical and thermal conductivity and is widely used in electronic terminals, connectors, and power semiconductor devices. Previous studies have demonstrated that an increased Ag content in solder alloys promotes the formation of Ag₃Sn IMC. The presence of Ag₃Sn suppresses metal atomic diffusion during EM. Consequently, the diffusion rate of interfacial IMCs is reduced, which suppresses the formation and growth of voids at the cathode side [11–14]. For example, Zhu et al. [15] reported that alloying 0.3 wt.% Ag into Sn–0.7Cu solder improved EM reliability, reducing the diffusion of interfacial IMCs by 26.7% under EM stressing. This improvement was attributed to the formation of Ag₃Sn pinned in both the bulk solder and the interfacial IMCs. Furthermore, compared with Sn–0.7Cu solder paste doped with 0.3 wt.% Ag nanoparticles, Sn–0.7Cu–0.3Ag solder prepared by element alloying exhibited more uniformly distributed Ag₃Sn particles. This microstructural feature more effectively impeded IMC diffusion and suppressed voids formation.

Although the effect of Ag content in solder alloys has been extensively studied, the influence of Ag supplied from surface finishes on EM behavior remains less well understood. In this study, we propose an approach to improve EM reliability by locally supplying a small amount of Ag from electroless nickel / electroless palladium / electroless silver (ENEPES) surface finish into Sn–0.7Cu solder. In this approach, electroless Ag plating is employed as an alternative to conventional immersion Au. This study also investigates how Ag thickness affects EM

reliability. Prior to the EM tests, preliminary experiments were conducted to determine appropriate Ag thickness conditions. In the preliminary study, the Ag thickness of the ENEPES was varied, and SJR was evaluated using ball pull (BP) tests and high-speed shear (HSS) tests. Solder wettability was further evaluated using wetting balance testing. Within the Ag thickness range of 0.05–0.2 μm , ENEPES exhibited BP performance comparable to that of ENEPIG. Although ENEPES showed slightly lower energy than ENEPIG in the HSS tests, its performance was still considered acceptable for practical applications. Furthermore, ENEPES demonstrated superior solder wettability compared with ENEPIG within this Ag thickness range. Based on these preliminary results, Ag thicknesses of 0.05 μm and 0.2 μm were selected as representative conditions for the subsequent EM reliability evaluation. The EM test results indicate that ENEPES effectively improves EM reliability in solder joints and offers new insights into the mechanisms responsible for suppressing IMC diffusion.

II. EXPERIMENTAL PROCEDURE

A. Surface Finish Formation

EM reliability was evaluated for three surface finish conditions: ENEPIG, ENEPES with an Ag thickness of 0.05 μm , and ENEPES with an Ag thickness of 0.2 μm (hereafter referred to as ENEPIG, thin-Ag ENEPES, and thick-Ag ENEPES, respectively). These surface finishes were formed on Cu pads with an opening diameter of 250 μm on FR-5 printed circuit board (PCB) substrates. The thickness of the Cu pads was approximately 20 μm . The thickness of each surface finish is summarized in Table 1. ENEPIG was composed of 0.06 μm -thick Au, 0.04 μm -thick Pd(P), and 7 μm -thick Ni(P) layers on the Cu pads. For thin-Ag and thick-Ag ENEPES, the underlying ENEP structure was identical to that of ENEPIG. The only difference was that the topmost Au layer was replaced with Ag layers of 0.05 μm and 0.2 μm , respectively.

TABLE I. COMPOSITION AND THICKNESS OF EACH SURFACE FINISH

Surface finish	Thickness (μm)		
	Au or Ag	Pd(P)	Ni(P)
ENEPIG	0.06	0.04	7
Thin-Ag ENEPES	0.05	0.04	7
Thick-Ag ENEPES	0.2	0.04	7

B. Electromigration Test Sample Fabrication

EM test samples were fabricated using these PCB substrates with ENEPIG and ENEPES surface finishes and Sn–0.7Cu solder balls with a diameter of 300 μm . The solder balls were mounted on the surface finishes by a reflow process with a peak temperature of 260 $^{\circ}\text{C}$, forming solder joints (Fig. 1). The samples had a daisy-chain structure with the same surface finish on both the top and bottom substrates (Fig. 2).

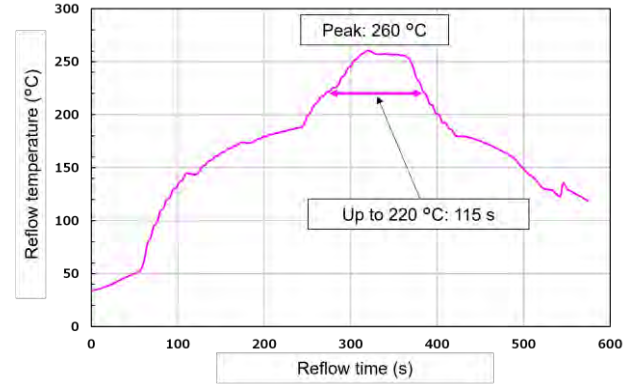


Fig. 1 Reflow temperature profile.

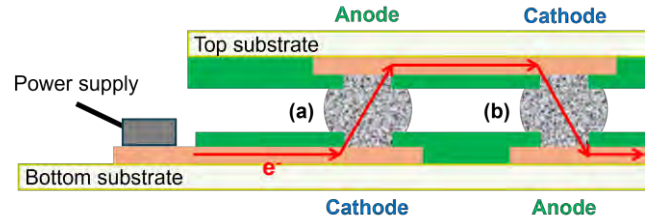


Fig. 2 Cross-sectional schematic diagram of the EM test sample.

C. Electromigration Test

During the EM tests, the bottom substrate side of each sample was connected to a power supply. The samples were placed in a chamber maintained at 150 $^{\circ}\text{C}$. A constant direct current was applied to achieve a current density of 14 kA/cm^2 in the solder joints. The electrical resistance was continuously monitored at 1 s intervals using a monitoring system connected to the power supply. Electron flow was from the bottom substrate side (cathode) of the solder joint in Fig. 2(a) to the bottom substrate side (anode) in Fig. 2(b), as shown by the red arrows. The time when the electrical resistance of the solder joint reached infinity was measured and defined as the mean time to failure (MTTF). For each surface finish, EM tests were performed on 15 samples, and the resulting MTTF values were compared.

D. Microstructural Characterization

Cross-sectional analyses were performed to investigate the morphology and elemental distribution of IMCs. The solder joint shown in Fig. 2(a) was observed with the bottom substrate facing upward. Microstructural analyses were conducted after EM stressing for 0 h (as-fabricated), 8 h, 20 h, and at MTTF (after failure) using field-emission scanning electron microscopy (FE-SEM, SU8600, Hitachi) and energy-dispersive X-ray spectroscopy (EDS, ULTIM EXTREME, Oxford Instruments).

III. RESULTS AND DISCUSSION

A. Electromigration Test Results

Fig. 3 shows the lognormal probability plots of the MTTF for 15 samples under each surface finish condition. For all surface finishes, the data points are approximately aligned along straight lines, indicating that the MTTF follows a lognormal distribution. The slopes of the fitted lines for ENEPIG and thick-Ag ENEPES are similar, indicating comparable data scatter. Compared with ENEPIG, the ENEPES plots are shifted to the right, indicating an improvement in MTTF. This shift is more pronounced for thick-Ag ENEPES. The average MTTF values summarized in Table 2 were 132.2 h, 162.0 h, and 231.9 h for ENEPIG, thin-Ag ENEPES, and thick-Ag ENEPES, respectively. These results suggest that ENEPES exhibits a longer MTTF than ENEPIG and that EM reliability improves with increasing Ag thickness. In particular, the average MTTF of thick-Ag ENEPES is 75.4% longer than that of ENEPIG, suggesting that the Ag layer contributes to EM suppression. In addition, thin-Ag ENEPES exhibits a 22.5% improvement in MTTF compared with ENEPIG, suggesting that even a thin Ag layer is effective in improving EM reliability.

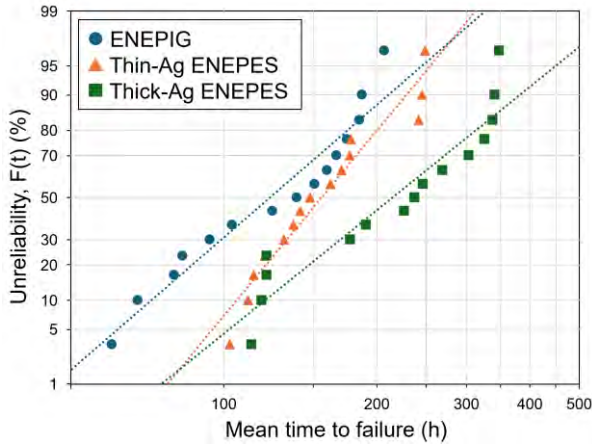


Fig. 3 Lognormal probability plots of the unreliability function for ENEPIG, thin-Ag ENEPES, and thick-Ag ENEPES.

TABLE II. AVERAGE OF MEAN TIME TO FAILURE

Surface finish	MTTF (h)
ENEPIG	132.2
Thin-Ag ENEPES	162.0
Thick-Ag ENEPES	231.9

B. Failure Analysis

Fig. 4 shows cross-sectional SEM images of ENEPIG, thin-Ag ENEPES, and thick-Ag ENEPES solder joints at 0 h of EM stressing and at MTTF. Fig. 4(a) and (b) correspond to ENEPIG, (c) and (d) to thin-Ag ENEPES, and (e) and (f) to thick-Ag ENEPES solder joints. The cathode and anode are placed at the upper and lower sides, and the red arrows show the direction of

electron flow. At 0 h of EM stressing, the Ni(P) layer remained on both the cathode and anode sides for all surface finishes. A thin and uniform $(\text{Cu,Ni})_6\text{Sn}_5$ layer was formed at the Ni(P)/Sn-0.7Cu interface. At MTTF, the Ni(P) and Cu layers on the cathode side were almost completely consumed by $(\text{Cu,Ni})_6\text{Sn}_5$ formation for all surface finishes. A thick $(\text{Cu,Ni})_6\text{Sn}_5$ layer accumulated on the anode side. On the cathode side, large voids formed due to metal atom depletion, which is considered the primary cause of failure.

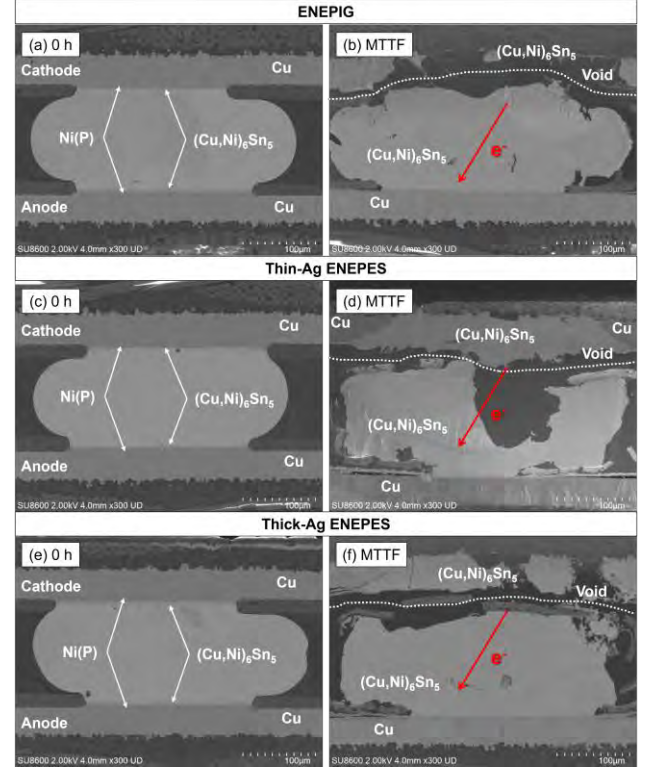


Fig. 4 Cross-sectional SEM images of ENEPIG, thin-Ag ENEPES, and thick-Ag ENEPES solder joints: (a, c, e) at 0 h of EM stressing (as-fabricated) and (b, d, f) at MTTF (after failure).

C. Microstructural Analysis of Ag_3Sn

To clarify the mechanism behind the improved EM reliability of ENEPES, the microstructure of the solder joints was examined in detail. Fig. 5 shows magnified SEM images of the thick-Ag ENEPES solder joints after EM stressing for 0, 8, and 20 h. The magnification was $\times 20,000$ for Fig. 5(a) at 0 h to clearly identify the thin interfacial Ag_3Sn layer. A lower magnification of $\times 5,000$ was used for Fig. 5(b) and (c) at 8 and 20 h, respectively. At 0 h, a P-rich Ni layer and a $(\text{Cu,Ni})_6\text{Sn}_5$ layer were observed on the remaining Ni(P) layer at the cathode side (Fig. 5(a)). In addition, a thin Ag_3Sn layer with a thickness of less than $0.1 \mu\text{m}$ was semi-continuously distributed along the surface of the $(\text{Cu,Ni})_6\text{Sn}_5$ layer. This Ag_3Sn layer is considered to act as a physical barrier that suppresses the growth and diffusion of interfacial IMCs. At this stage, Ag_3Sn was locally present near the $(\text{Cu,Ni})_6\text{Sn}_5/\text{Sn}-0.7\text{Cu}$ interface. After 8 h of

EM stressing, Ag_3Sn particles with a thickness of approximately $0.3\text{ }\mu\text{m}$ were observed to detach from the cathode side and disperse into the bulk solder. These particles appeared either as isolated particles or attached to Ni–Sn IMC particles ($\text{Sn at}\% \approx 90\%$), as shown in Fig. 5(b). These observations suggest that part of the Ag_3Sn layer, which was semi-continuously distributed along the $(\text{Cu},\text{Ni})_6\text{Sn}_5$ layer at 0 h, diffuse into the bulk solder while remaining partially attached to fragments of the $(\text{Cu},\text{Ni})_6\text{Sn}_5$ layer. The high Sn content in the Ni–Sn particles may result from reactions with the surrounding Sn during this diffusion process. S. Ismathullakhan et al. reported that Ag_3Sn particles dispersed in the bulk solder act as barriers to metal atom diffusion. After 20 h of EM stressing, the Ag_3Sn particles grew and coarsened, forming large aggregates in the bulk solder with a maximum size of approximately $3.6\text{ }\mu\text{m} \times 3.2\text{ }\mu\text{m}$ (Fig. 5(c)). These observations indicate that Ag_3Sn particles dispersed in the bulk solder continue to diffuse and aggregate as the EM stressing time increases. This diffusion and aggregation behavior is consistent with the findings of M. Lu et al., who reported the coarsening of Ag_3Sn after EM stressing. A similar behavior of Ag_3Sn is expected in thin-Ag ENPEPS solder joints during 0–20 h. However, direct observation using FE-SEM and EDS was difficult due to the low Ag content.

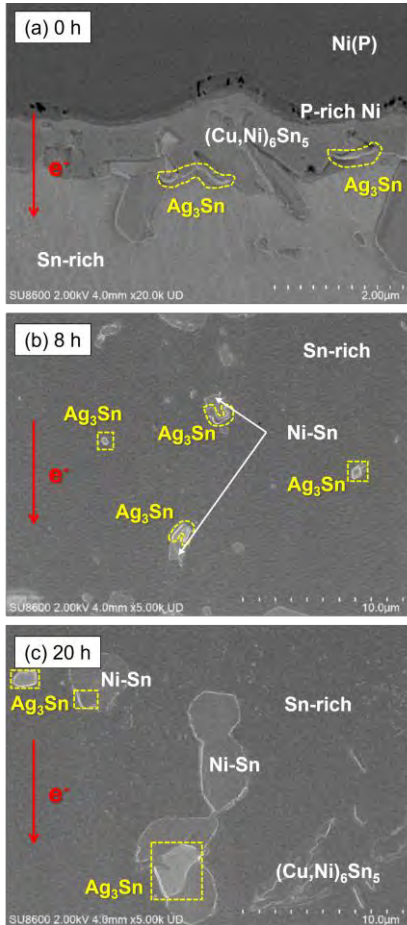


Fig. 5 SEM images of Ag_3Sn microstructure at different EM stressing times: (a) cathode side at 0 h, (b) bulk solder at 8 h, and (c) bulk solder at 20 h.

To better understand differences in EM behavior at the interfaces of Sn–0.7Cu solder with different surface finishes, schematic diagrams of ENEPIG and thick-Ag ENPEPS/Sn–0.7Cu interfaces are shown in Fig. 6. In ENPEPS, a thin Ag_3Sn layer is locally formed and pinned at the interface between the Sn–0.7Cu solder and the cathode-side $(\text{Cu},\text{Ni})_6\text{Sn}_5$ layer. At the initial stage of EM stressing, this Ag_3Sn layer suppresses IMC growth and diffusion (Fig. 6(b)). As EM stressing proceeds, the layer becomes dispersed as particles in the bulk solder, thereby continuously inhibiting IMC diffusion. In contrast, in ENEPIG, no such layer exists to suppress IMC growth and diffusion, allowing EM to proceed more readily (Fig. 6(a)). As a result, ENPEPS exhibits superior EM reliability compared to ENEPIG.

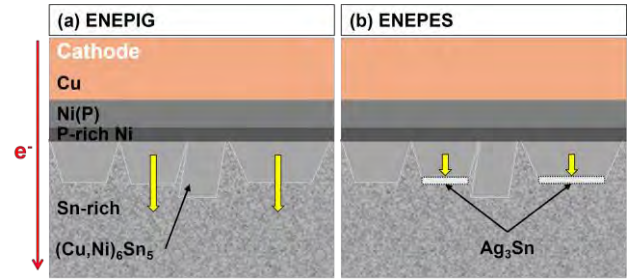


Fig. 6 Schematic diagrams of Ag_3Sn layer behavior at the (a) ENEPIG and (b) ENPEPS/Sn–0.7Cu interfaces.

In Ag-containing solder alloys, Ag is uniformly distributed throughout the solder balls. Therefore, it is inferred that only a small fraction of the total Ag is consumed in the formation of Ag_3Sn near the surface finish/solder interface. Consequently, the utilization efficiency of Ag_3Sn for suppressing IMC growth at the interface may be limited. In contrast, even if the $0.05\text{ }\mu\text{m}$ and $0.2\text{ }\mu\text{m}$ Ag layers of ENPEPS were to completely diffuse into the Sn–0.7Cu solder balls, the resulting total Ag content in the solder joint would be only approximately 0.025% and 0.1%, respectively. Despite these extremely low Ag concentrations, ENPEPS shows a marked improvement in MTTF compared to ENEPIG. This improvement is attributed to the localized and efficient supply of Ag to the surface finish/solder interface. In this study, the improvement in EM reliability by ENPEPS was clearly demonstrated using Sn–0.7Cu solder. On the other hand, the effect of ENPEPS on EM reliability in Ag-containing solder joint remains an interesting topic. One such case is when only 0.1% of Ag is supplied from ENPEPS to SAC305 solder containing 3% Ag. In particular, the correlation between Ag_3Sn distribution and EM reliability should be investigated in detail. Such analyses are expected to provide further insight into how the Ag source and supply mode influence the improvement of EM reliability.

IV. CONCLUSION

In this study, EM reliability of conventional ENEPIG and ENPEPS surface finishes with Ag thicknesses of $0.05\text{ }\mu\text{m}$ and $0.2\text{ }\mu\text{m}$ was compared. Sn–0.7Cu solder was employed to investigate the influence of Ag supplied from the surface finish on the EM behavior of solder joints. EM tests revealed that ENPEPS exhibited superior EM reliability compared with

ENEPIG. The MTTF of ENEPES with Ag thicknesses of 0.05 μm and 0.2 μm increased by 22.5% and 75.4%, respectively, compared with ENEPIG. After EM tests, similar failure modes were observed for all three surface finishes. Along the electron flow direction, Ni(P) and Cu diffused from the cathode side and reacted with Sn to form $(\text{Cu,Ni})_6\text{Sn}_5$, which accumulated at the anode side. Large voids resulting from metal atom depletion were observed at the cathode side. Microstructural observations at the $(\text{Cu,Ni})_6\text{Sn}_5/\text{Sn}-0.7\text{Cu}$ interface revealed that, in ENEPES solder joints, a thin Ag_3Sn layer was locally and semi-continuously formed along the surface of the $(\text{Cu,Ni})_6\text{Sn}_5$ layer. Despite the extremely small amount of Ag supplied from ENEPES, the improved EM reliability compared with ENEPIG is attributed to the effective suppression of IMC growth and diffusion by the thin Ag_3Sn layer. Preliminary evaluations further indicated that ENEPES with Ag thicknesses in the range of 0.05–0.2 μm exhibits ball pull performance comparable to that of ENEPIG, slightly reduced but acceptable high-speed shear performance, and improved solder wettability. These results suggest that ENEPES has strong potential as an alternative surface finish to ENEPIG for solder joints in electronic packaging applications.

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