INVESTIGATING THE IMPACT OF FINAL FINISHES ON THE INSERTION LOSS IN AS RECEIVED AND AFTER AGING

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Abstract
The task of the final finish on the printed circuit board is to protect the copper surface and at the same time keep it active for the subsequent assembly steps. In high frequency applications, additionally the impact on the signal loss becomes of interest.
Typically, the choice of the final finish is defined by the target application. The demands on solderability and bondability need to be considered and the acceptable price level needs to be defined. For the use in high frequency applications the signal integrity becomes of interest and adds on the reliability criteria such as solder joint reliability or corrosion resistance.
In this study various surface finishes were tested towards their performance on insertion loss at high frequency. In contrast to earlier studies the frequency range was investigated up to 150 GHz and the impact of thermal or humid aging of the final finish was evaluated. Overall, seven different finishes have been selected including EPAG (Electroless palladium/Autocatalytic gold), I-Sn (Immersion tin), I-Ag (immersion silver), DIG (direct immersion gold), Au/Pd/Au (Gold/Palladium/Gold), ENIG (Electroless Nickel/Immersion Gold) with high and medium phosphorous Nickel and ENEPIG (Electroless Nickel/Electroless Palladium/Immersion Gold).
The paper compiles the data for insertion loss versus frequency for the different final finishes at layer thicknesses as commonly used in the PCB industry. The results in the insertion loss performance are correlated to other properties of the different final finishes such as reliability and assembly performance to identify the best candidates for high frequency applications.

Key words
High Frequency, 5G, Fine Pitch, signal transmission, final finish, signal loss

I. Introduction
In the electronics industry a trend for moving to higher frequency ranges is observed, which is driven by the increased data traffic and higher requirements on connection density. This is connected to developments such as autonomous driving, increasing mobile communication or IOT (internet of things). With moving to higher frequencies new characteristics of the PCB build up become important as the skin effect becomes a critical factor for the thin film interconnections.[1] The total insertion loss is thereby a sum of the four contributors: conductor, dielectric, radiation, and leakage. [2]
The task of the final finish in general is to prevent the copper track from oxidation and contamination and provide an active surface for the subsequent assembly steps. Various final finishes are available in the market which all exhibit specific benefits and weaknesses. The type of final finish is typically chosen based on the assembly requirements, the

needs for corrosion resistance, the fine line capability and finally the process cost. While OSP and Immersion Silver provide solderable surface protection for comparably lower cost, the final finishes that contain precious metals like ENIG, ENEPIG, EPAG, Au/Pd/Au or DIG provide a bondable surface in addition. Beside that the precious metal containing final finishes exhibit benefits regarding assembly as they provide multiple solderable and wire bondable surfaces. The impact of the final finish on the signal transmission has been studied by various teams leading to a main finding, that the presence of nickel in the final finish has the most significant impact on the signal loss. [1,3-5]. The intention of the study presented in this paper is to evaluate the final finish impact for frequency ranges above 100 GHz up to 150 GHz. As in high reliability applications multiple soldering and harsh environment exposition also needs to be considered, additional measurements were performed on the final finishes which were exposed to reflow- and humidity aging before the measurement.

II. Experimental procedures

A. Test substrate design

The experiments used microstrip lines on an Isola Astra MT77 base material with a specified relative permittivity of Dk = 3 and a loss tangent Df = 0.0017. Figure 1 shows a cross-section illustration of the microstrip structure. The design parameters of the microstrip are as follows: trace thickness t = 0.02mm, substrate height h=0.125mm, and two trace width variants were implemented. The first variant had a width of w = 0.285mm, resulting in a 50 Ω characteristic impedance, while the second variant had a width of w = 0.13mm, resulting in a characteristic impedance of 75 Ω.

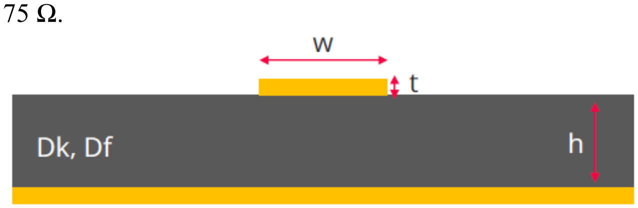

Figure 1: test substrate design

The microstrip line serves the purpose of extracting its propagation constant for various surface finishes. The propagation constant characterizes the attenuation and phase properties of the transmission line. To extract the propagation constant, we utilized the multiline method [6]. Our measurement approach involved designing and manufacturing multiple microstrip lines of varying lengths. The lengths chosen in this work are 0, 0.5, 1, 3, 5, and 6.5 mm, which can support frequencies ranging from 1 GHz to 150 GHz. These lengths are relative lengths where the first microstrip line serves as the reference zero length.

B. High frequency measurements

We performed the measurements using a semi-automatic 200mm wafer prober FormFactor Summit200, in conjunction with a VectorStar vector network analyzer (VNA) from Anritsu, which had additional mmWave extenders allowing for measurement up to 150 GHz. FormFactor ACP ground-signal-ground (GSG) RF probes established the interface between our measurement equipment and the microstrip lines. Since the probes can only measure structures in GSG configuration, a tapered pad for the microstrip was designed to enable broadband measurement, following the procedures outlined in [7]. A photo of the measurement setup can be seen in Figure 2.

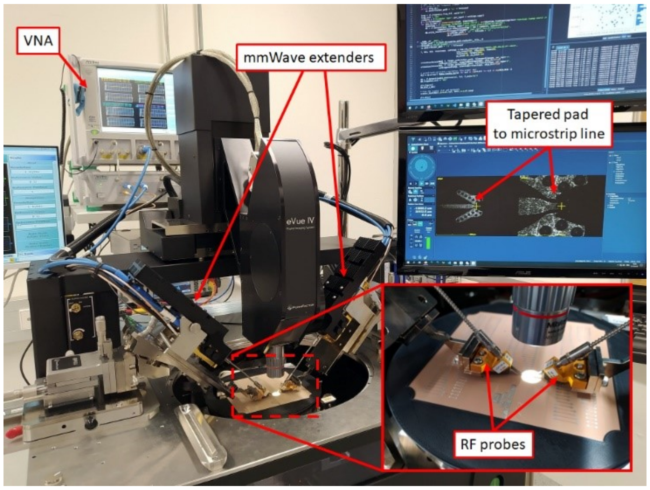

Figure 2: measurement setup

The VNA was configured to measure in frequency range from 1 GHz to 150 GHz, with an IF-bandwidth of 1 kHz and power level of -10 dBm. The lower frequency limit had to be set at 1 GHz because the multiline method used to extract the propagation constant requires extremely long transmission lines to cover lower frequencies below 1 GHz, which is not feasible with the micro positioner of the wafer prober used for the measurement.
To improve the quality of the parameter extraction process, each microstrip line was measured for a 100 times to establish an average result and reduce the noise influence of the VNA, especially at the mmWave range.
After performing the multiline procedure to extract the propagation constant γ, the loss per unit length is determined through the following conversion equation:

$$\text{Loss} = \frac{20 \times 10^{-3}}{\ln 10} Re(\gamma) \quad (\text{dB/mm})$$

C. Final finish selection, aging and cross sectioning

8 different types of final finishes were selected for the study which were applied with standard coating thickness as used in the industry.

Table 1: overview of surface finish types

Final Finish type	Layer thickness in µm
Bare copper reference	
ENIG (mid-P Ni)	4-5µm Ni, 0.04-0.05µm Au
ENIG (high-P Ni)	4-5µm Ni, 0.04-0.05µm Au
EPAG	0.1-0.15µmPd, 0.1-0.15µm Au
I-Sn	0.9-1.1µm Sn
ENEPIG (pure Pd)	4-5µm Ni, 0.1-0.15µm Pd, 0.1-0.15µm Au
I-Ag	0.1-0.3µm
DIG	0.1-0.3µm
Au/Pd/Au	0.02-0.04µm Au, 0.1-0.15µm Pd, 0.1µm Au

To simulate the exposure of the final finish in the assembly process, the samples were measured in three different conditions:
1) As received
2) After 3x reflow aging
3) After 3x reflow aging + IPC humidity aging 8h@72°C/85%rel. Humidity followed by 1h@105°C
Cross sectioning of the aged samples was done by focused ion beam (FIB) followed by FE-SEM imaging using a FEI Helios Nanolab 660.

III. Results

Comparing the signal loss for the different types of final finishes with the bare copper reference, the finishes can be categorized into three groups: precious metal finishes, immersion tin and silver finishes and the Ni-containing finishes.

A. The precious metal finishes

Figure 3 shows the permittivity and loss on a 50 ohm strip in a frequency range from 1 to 150 GHz with the reference colored in black.
The measurement shows clearly that all three finishes have no impact on the signal loss performance. As a matter of fact, the measured values are in the same range like for the bare copper reference.

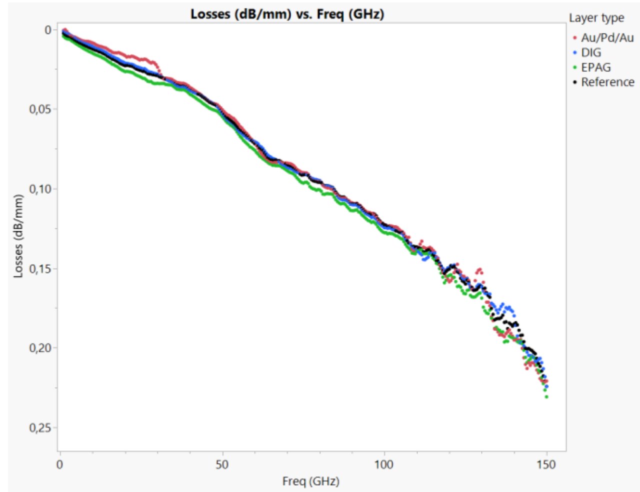

Figure 3: Signal loss comparison for EPAG, DIG, Au/Pd/Au and Cu-Reference

B. The immersion tin and silver layers

The measurements of the I-Sn and I-Ag layer clearly indicate, that with an increasing layer thickness of a less conductive metal, the signal transmission is reduced. While the thin silver coating performs like the thin Pd- and Au layers, the I-Sn layer leads to a detectable degradation of the signal transmission. This is constant over the full frequency range from 30 to 150 GHz indicating, that the 1µm thick and lower conductive tin layer exhibits a significant impact.[10]

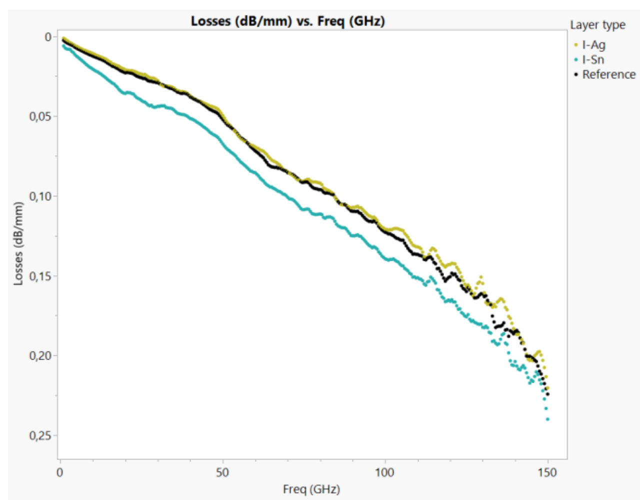

Figure 4: Signal loss comparison for I-Sn and I-Ag and Cu-Reference

C. Ni-containing finishes

As the conductivity of nickel is lower compared to palladium or gold [10,11], there are concerns on the use of nickel containing final finishes in high frequency applications.

In this comparison, three types of nickel finishes were tested: two ENIG layers with mid and high P-content in the nickel layer and an ENEPIG layer. The mid-P ENIG exhibits a P-content of 6-10% in the nickel layer, while the high-P Nickel layer contains 11-12% P in the nickel layer. For the ENEPIG layer a mid-P electroless nickel layer was combined with a pure palladium deposit. Figure 5 shows the measurement on the 50ohm microstrip.

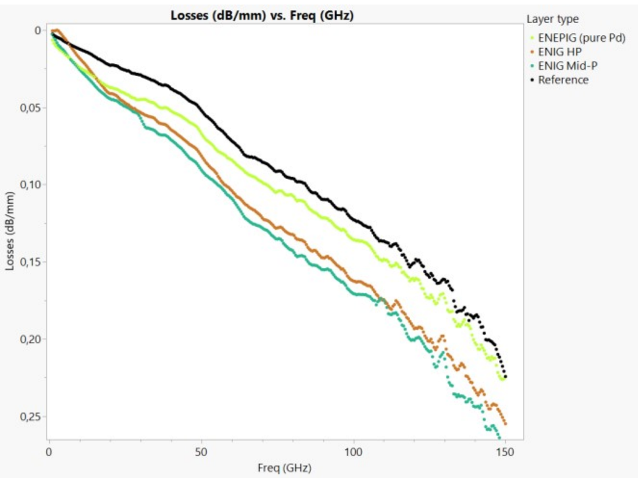

Figure 5: Signal loss comparison for mid- and high P ENIG, ENEPIG and Cu-Reference

The results show, that the ENIG layers exhibit the strongest signal loss of all the final finish types in this test round. A slight trend can be observed that this effect is less pronounced for the high-P ENIG finish.
In contrast to that the ENEPIG finish shows a very low impact on the signal transmission. In fact, the signal loss measured for ENEPIG is in a similar range as for the EPAG finish and just a minor impact of the nickel layer can be recognized. In the direct comparison of these two finishes in figure 6, this observation becomes more obvious.

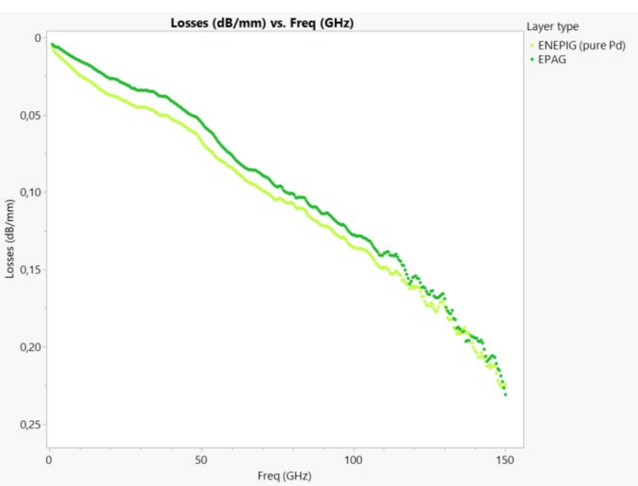

Figure 6: Signal loss comparison for ENEPIG and EPAG

At higher frequencies the curves are approaching and reach similar values for frequencies above 120 GHz. This can be explained by the skin depth, which at these high frequencies becomes low enough, so that the impact of nickel gets negligible.

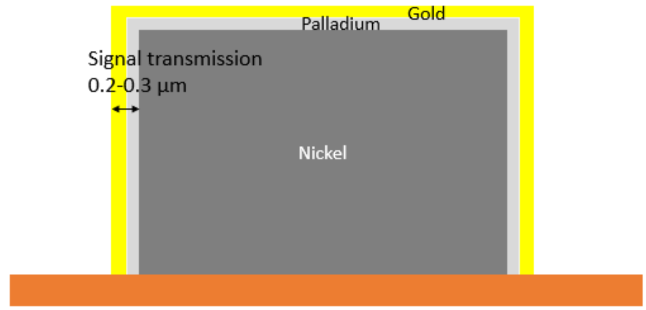

Figure 7: Signal transmission in ENEPIG through Pd- and Au-layer

To evaluate if the aging of the final finish in the assembly process or in harsh environment has an impact on the signal transmission, the same measurements were conducted on samples which were artificially aged. The graphs shown in following figures represent the results for as received conditions and after reflow and thermal aging.
For the Nickel free precious metal coatings atmospheric corrosion can be considered as potential risk which could lead to defects at the copper/precious metal layer interface and with that to a potentially reduced signal transmission.
Comparing the aged samples with the as received layers, no difference in the signal transmission could be detected. The aged samples performed in the same way as in the as received condition and can ensure reliable signal transmission also after reflowing or humid aging.

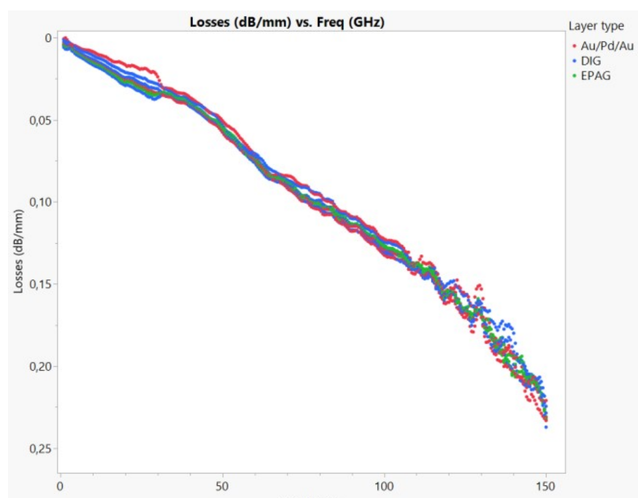

Figure 8: Signal loss comparison for EPAG, DIG, Au/Pd/Au after aging

For I-Sn and I-Ag a similar picture is observed. For both final finishes the impact of the reflow aging or humidity aging can be neglected. For all condiditons a slight gap is observed between I-Sn and I-Ag results, but the variation within the two types of final finishes are low and not impact of the artificial aging can be observed.

The FIB cross section of I-Sn after reflowing and humid aging shows, that the intermetallic phase between copper and tin has been fully developed and penetrates the full layer thickness up to the layer surface. The signal loss measurements confirm that the IMC formation has no impact on the signal transmission and that the defect free layers perform similar to the as received conditions.

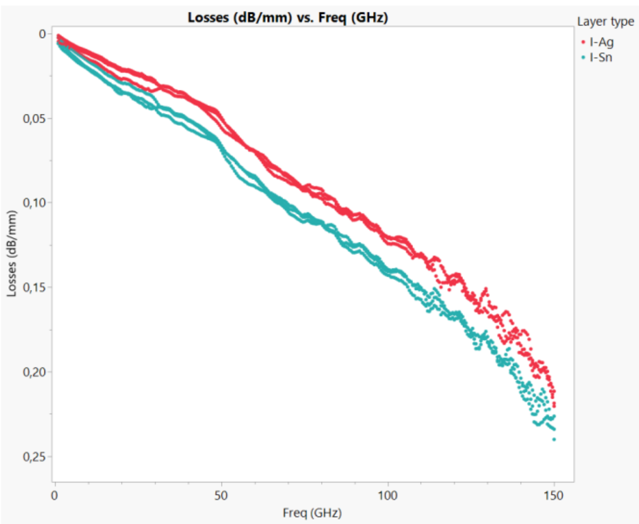

Figure 9: Signal loss comparison for ISn and IAg after aging

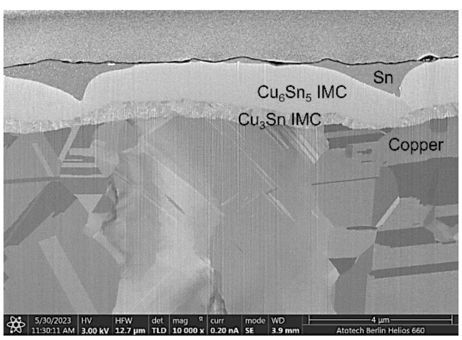

Figure 10: FIB cut of the I-Sn layer after 3x reflow + humid aging

For the nickel containing finishes again a different situation can be observed for ENIG and ENEPIG. While the effect of the aging in negligible for ENEPIG, some deviation in the signal transmission can be observed for the ENIG finishes.

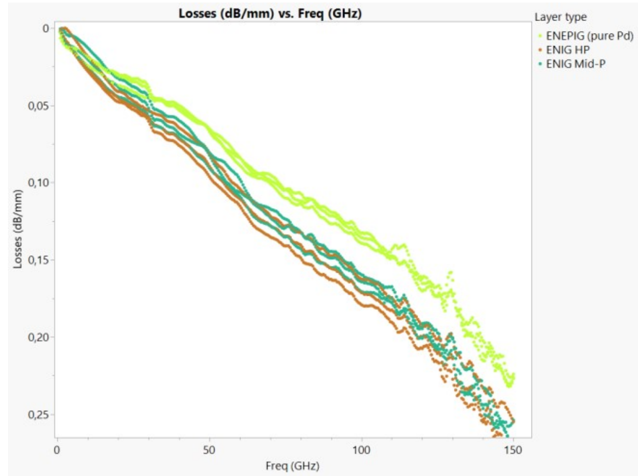

Figure 11: Signal loss comparison for mid- and high P ENIG, ENEPIG after aging.

The consistency of the ENEPIG can be explained by the skin depth effect as observed in the as received measurement. As the nickel layer is not involved in the signal transmission, the deviation which is observed in the ENIG finishes appears to be related to the nickel layer.

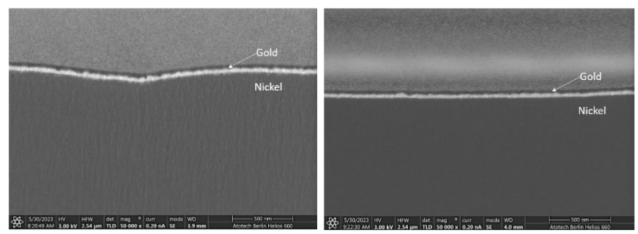

Figure 12: FIB cut of the mid-P ENIG (left) and high-P ENIG layer (right) after 3x reflow + humid aging

Nevertheless, the deviation in the signal transmission for ENIG after aging is small and the cross sections do not indicate a defect that could act as an explanation for the variation. Further studies are required, to verify and to identify the root cause of these deviations.

IV. Comparison of final finish properties

Summarizing the observations on the signal transmission properties of the different final finishes, following statements can be made:

A. The precious metal finishes

For all precious metal final finishes like EPAG, DIG or Au/Pd/Au the impact of the final finish on the signal transmission is negligible. They all perform comparable to the bare copper trace over the full frequency range and no negative impact of thermal or humid aging can be detected. All finishes offer the benefit of fine line capability due to the overall low layer thickness and are wire bondable and solderable. Due to the intermetallic formation with copper a highly reliable solder joint is formed, which was confirmed in comparison for other finishes for EPAG in particular. [8]

B. Immersion tin and Immersion silver

Comparing I-Sn and I-Ag the I-Ag layer performs slightly better regarding the signal transmission. This finding can be explained by the lower conductivity of tin compared to silver, and by the higher thickness that is deposited for the immersion tin layer. Both final finishes are multiple solderable, nevertheless immersion tin layers provide the benefit of corrosion resistance towards harsh environments that is significantly better compared to immersion silver [9] and by that are a preferred choice in the automotive industry.

C. Ni-containing finishes

The ENIG layers showing the highest signal loss related to the presence of nickel in the layer. Even though ENIG is a mature and widely used solderable and Al-wire bondable finish, it might therefore not be the first choice for high frequency applications. Due to the decreasing skin depth, the impact of the nickel layer on the signal loss is almost negligible for ENEPIG. It shows a comparable signal loss performance like I-Sn. Offering the benefits of wire bondability and highest solder joint reliability, it can be the preferred choice over I-Sn when wire bonding is required.

V. Conclusion

A comparative study of signal transmission measurement was performed on different types of final finishes. To simulate the conditions in the assembly process, the final finishes were thermally aged and exposed to temperature and humidity. EPAG, DIG, Au/Pd/Au and I-Ag performed best in signal transmission. As slight drop was observed for I-Sn. The ENIG layers showed the largest signal loss of all tested final finishes. The impact of ENEPIG was on a comparable level to I-Sn, which can be explained by the reduced skin depth and the signal moving to the outer edge of the finish which in this case is the Pd/Au layer. The nickel layer in the ENEPIG finish does not contribute to the signal transmission so that ENEPIG final finish can be considered as high reliability finish for high frequency applications. The impact of the thermal or humidity aging was found to be negligible and no negative impact on the signal transmission was observed.

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