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The Impact of the Gold Layer Thickness on Layer Properties, Reliability and Solder Wetting Performance of an ENIG Finish

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ABSTRACT
The ENIG finish is one of the most mature final finishes accepted in the market for decades. ENIG stands for "electroless nickel – immersion gold" where the gold is applied by either fully immersion reaction or mixed (autocatalytic supported) reaction type electrolytes. With the increasing cost pressure in the PCB industry, due to its higher precious metal cost the gold layer in the ENIG finish gets into focus. In this context lowering the target thickness of the gold layer might be considered as one option to cut down the overall process cost. In order to not sacrifice the final finish performance, it needs to be ensured that the solderability and solder joint reliability is not affected by the reduced gold thickness. This is also addressed by industry standards such as the IPC 4552 for ENIG finishes which specifies thickness the ranges for the final finish.

The purpose of this study was to evaluate the impact of the gold layer thickness on the ENIG layer performance in different perspectives. As part of the study it was investigated, how the difference in gold layer thickness can be reflected in layer analysis after thermal curing of the final finish. Therefore, the ENIG layers of different gold layer thickness were subjected to varying curing times and temperatures and the layers were analyzed in regard to their chemical composition. Additionally, the correlation of gold layer thickness and ENIG layer soldering performance was investigated. For the evaluation of the soldering performance, different types of soldering tests were selected which allow a judgement of the solder wetting behavior of the final finish as well as the reliability of the solder joint. The results collected in this study show that a lower limit value must be recommended for the gold layer thickness in order to ensure sufficient functionality of the final finish. It can be shown that with decreasing gold layer thickness an increased migration of nickel to the surface after thermal curing can be observed. This can lead to the formation of oxides on the surface which may inhibit the solder wetting and formation of the intermetallic compound with the nickel layer. The finding is in line with the soldering results, that indicate a better solder wettability can be achieved with increasing gold layer thickness.

Key words: ENIG; Surface finish; Solder Joint; Solder wetting; IMC; Gold layer.

INTRODUCTION
The main task of the final finish is to protect the copper pad from tarnishing or oxidation but at the same time keep the surface active for the assembly. Electroless nickel/immersion gold (ENIG) is a widely accepted finish in the market which provides a good solderability and capability for Al-wire bonding. During the soldering process the intermetallic phase is formed between the nickel and the solder alloy. This can be inhibited by oxide formation, which inhibits the growth of the intermetallic compound (IMC) and with that the connection between the nickel layer and the component.; A main function of the gold layer is to prevent the oxidation of the nickel layer. Typically, the deposit thickness follows the recommendations such as specified in the IPC 4552 which suggests an acceptable minimum gold thickness as $x_{mean} - 3\sigma \geq 0.04$ µm. As a potential answer to the increasing demand for cost reduction in the printed circuit board (PCB) industry, it might be considered to lower the gold target thickness in order to reduce the precious metal cost of the finish. The potential risks of too low gold thickness and the correlation of gold thickness and solder wettability of the ENIG finish are discussed in this paper.

IMMERSION GOLD LAYER PROPERTIES AND IMPACT ON SOLDER WETTING

Experimental
Process flow
All tests were conducted on internal test panels with test structures for the soldering evaluation. The plating of the different finishes was performed in a plating line following the process flow as given in table2.

Table 1 Process flow of the plating process

Process Step	T [°C]	t [min]
Acidic Cleaner	40	5
DI Rinse	RT	1
DI Rinse		1
DI Rinse		1
Etch Cleaner	35	2
DI Rinse	RT	1
DI Rinse		1
DI Rinse		1
PreDip	RT	3
Pd Activation	23	1,5
DI Rinse	RT	1
DI Rinse		1
DI Rinse		1
Mid-P Nickel	80 - 85	20 – 25
DI Rinse	RT	0,5
DI Rinse		0,5
DI Rinse		0,5
Gold	75-85	varying
DI Rinse	RT	1
DI Rinse		1
Hot Rinse	50	2
Dryer	60	15

Thickness measurement and P-content (%w/w)

All deposit thicknesses were measured by means of X-ray fluorescence (XRF) using a Fischer XDV-µ.

SEM imaging

The structural characterization of the layers was conducted by using scanning electron microscopic (SEM) imaging with a FEI Nova Nanolab FIB (Focussed ion beam) instrument.

Solderability and solder joint reliability

To evaluate the solderability a *solder wetting tests* were performed using Senju M31-GRN360-KV (LF) paste. Reflow was performed in Rehm Compact Nitro B 2100-400 oven under air atmosphere for the wetting tests.
The evaluation was done at the optical microscope Olympus SZX16.
Further details on the evaluation are mentioned in the respective section.

Results

The gold plating electrolytes applied for ENIG finishes can be categorized in immersion type gold electrolytes and mixed reaction immersion gold electrolytes. For the immersion gold electrolytes, the deposition is fully driven by the immersion reaction to dissolve nickel to provide the electrons for the gold plating. To reduce the immersive attack to the nickel there are also electrolytes available, which work with a mixed reaction mechanism. Depending on the type of additive or reducing agent, the ratio of immersion/autocatalytic reaction can vary. The results presented in this paper focus on the evaluation of gold electrolytes with high immersion character and low autocatalytic properties.
Figure 1 shows the plating thickness over time in correlation to the plating temperature.

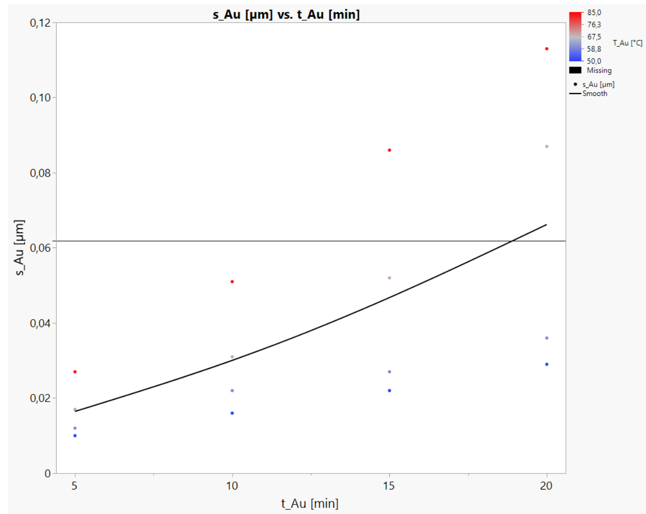

Figure 1: impact of temperature and time on plating thickness of gold layer

The plating rate and deposit thickness strongly depends on the temperature of the electrolyte. A decrease of the temperature by just 15°C can lead to a reduction of the deposit thickness of 20%. The effect is even higher at lower dwell times so that at 10 minutes plating time the same drop in temperature lead to a reduction of 40% in the layer thickness. In the early stage of the gold deposition the gold coverage is poor. To check the structure and coverage of the gold layer surface scanning electron microscopy images were performed for different layer thicknesses. In order to ensure a slow and homogeneous deposition the gold layers were deposited at mild conditions with a low temperature of 50°C.

10 nm

41 nm

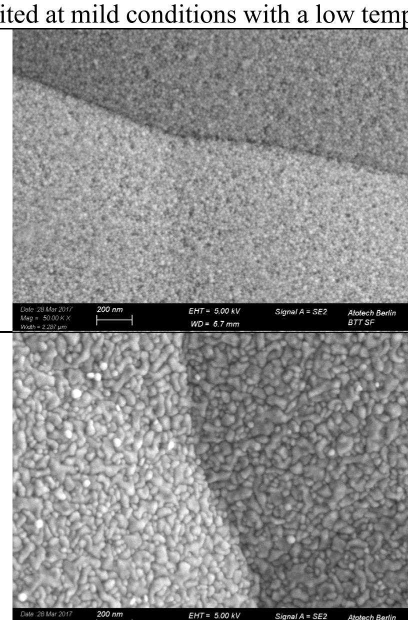

Figure 2: SEM surface image of gold structure

On the top picture a very fine crystalline deposit of the gold can be observed, that is evenly covering the nickel but leaves open spots not forming a dense layer yet. With 40 nm the layer is closed with even crystal formation covering the nickel surface. To confirm the findings of the SEM investigations, electrochemical porosity studies have been performed by means of chronoamperometry. For this a sample plated with ENIG was exposed to an acidic solution and the current measured over time. The measurement was done with a Potentiostat/Galvanostat Model 263 by EG&G Princeton Applied research with a voltage of 0.2 V applied for 600 seconds. The measurement area was 0.785 cm² and an Ag/AgCl 3MKCl electrode was used as reference electrode. 5 Vol% sulfuric acid was used as electrolyte. Figure 3 shows the current measured for varying gold layer thicknesses over after 600 seconds. A higher current value indicates a higher porosity of the gold layer. The graph shows that with low Au thickness the measured current can vary over a wide range while at 0.05 nm the gold layer appears to be dense enough to ensure a good protection against the corrosive attack of the acidic electrolyte.

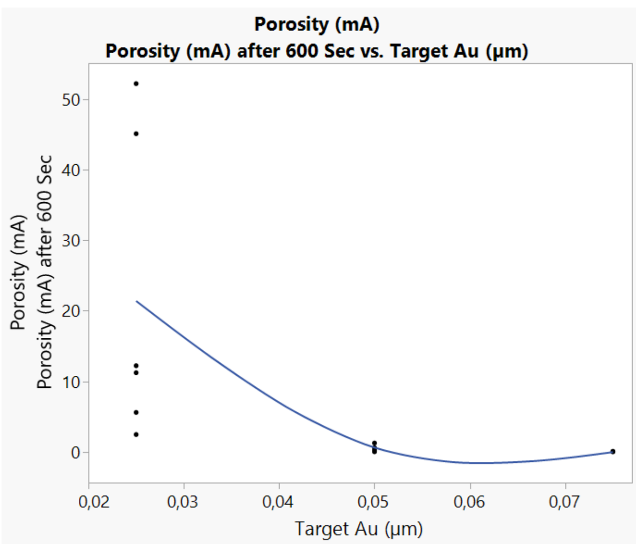

Figure 3: porosity measurement of ENIG with varying gold layer thickness

To investigate the impact of the gold layer thickness and potential porosity on its capability to prevent the nickel layer from oxidation, a post bake step was applied to the ENIG deposit and an EDX analysis was performed on the surface. The post bake step was applied for 30 and 120 minutes at 150°C. This test was performed with varying gold thickness of 40, 70 and 90 nm to compare the Ni- and O-content which can be detected on the gold surface. In Figure 4 the results detected for nickel and oxygen on the ENIG surface are plotted versus the gold layer thickness and the curing time. It shows, that with increasing curing times, higher contents of nickel and oxygen can be detected. With a low gold thickness already without the curing nickel oxides can be observed at the ENIG surface. With additional thermal exposure these values increase significantly. A gold layer thickness of 70 nm already provides a denser coverage so that less nickeloxides can reach the surface. The difference is most obvious between 40 and 70 nm, while the 90 nm thickness results in a similar performance like the 70 nm.

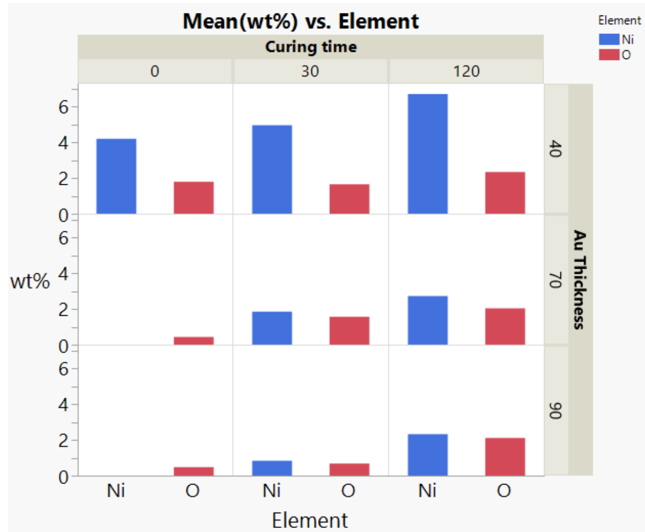

Figure 4: EDX measurement of Ni and O on ENIG after thermal curing

Summarizing the results of the SEM-investigation, the porosity studies and the EDX-measurement it can be concluded, that with decreasing gold thickness the gold layer gets porous and can be permeable towards the migration of nickel and nickeloxides to the ENIG surface. To study the impact of the nickeloxides on the formation of solder wetting, different solder wetting tests have been performed. Figure 7 shows exemplary test results that were received with ENIG layers plated with 40, 80 and 90 nm gold. In the solder spread test solder depots of 1000µm diameter are printed to the pad and reflowed. After the reflow step the wetting angle is determined. Typical pass criteria require a wetting angle of <20° for as received conditions and <25° after aging. The lower the wetting angle is, the better the solder spreading on the surface.

Beside the solder spread also solder indicator and solder gap test were performed. In the solder indicator test the solder is printed in triangle shape on a rectangular pad and it is measured, how far the solder connects after the reflow process. In this case higher values represent better solderability.

Figure 5 shows the design of test pad and solder depot.

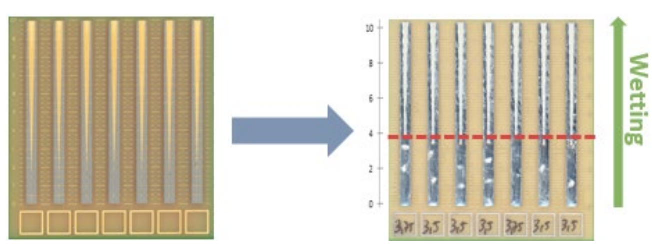

Figure 5: test design for solder indicator test

The solder gap test is a similar test where solder depots are printed on line structures with increasing gaps between the solder depots. Figure 6 shows the test structure. The more far the solder connects and can bridge the gaps, the better the solderwetting is.

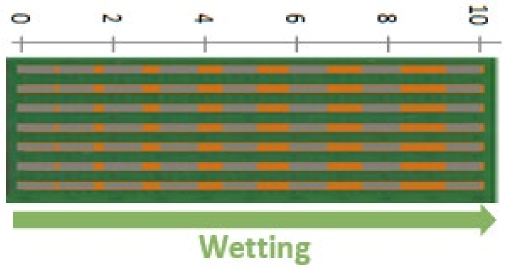

Figure 6: test design for solder gap test

The results given in the figure below show the solder wetting after humid aging and after two times reflow aging.

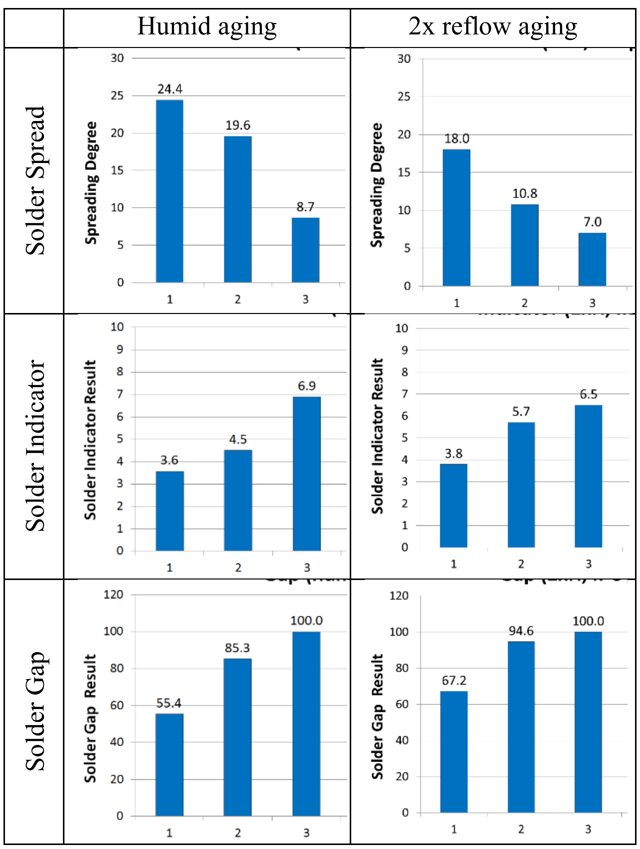

Figure 7: Solder wetting results for different gold layer thickness of 40 (sample 1), 70 (sample 2) and 90 (sample 3) nm

All the tests that were performed show confirm the same trend that with increasing gold thickness a better solder wetting can be achieved. Even though also the ENIG layers with a gold thickness of 40 nm can fulfill the acceptance criteria for the respective tests, an improved wettability with high gold thickness can be clearly confirmed. As the investigation of the gold layer structure related to the gold layer thickness shows, that there is a risk for higher porosity at low gold thickness and an increased migration of nickel to the ENIG surface where nickel oxides are formed. This nickel oxide formation can inhibit the formation of the Cu/Sn intermetallic and by that bear the risk for soldering defects. This is reflected in the reduced wetting performance at the lower end of the low gold thickness values.

To mitigate this risk of soldering defects for ENIG layers with a gold layer thickness at the lower end of the specification, a post treatment can be applied to remove nickel oxides from the surface before the ENIG layer is assembled. The post treatment solution contains of acidic components which can dissolve the nickel oxides at the surface and wetting agents which at the same time ensure a good and homogeneous coverage on the ENIG surface. Thorough rinsing after the cleaning stable ensures that no residues remain on the ENIG layer, and the layer can be dried and packed or assembled afterwards. Solder spread tests performed on samples which where thermally cured for 8 hours at 150°C showed, that the solder spread angle can be decreased to similar values as they are achieved before the thermal aging.

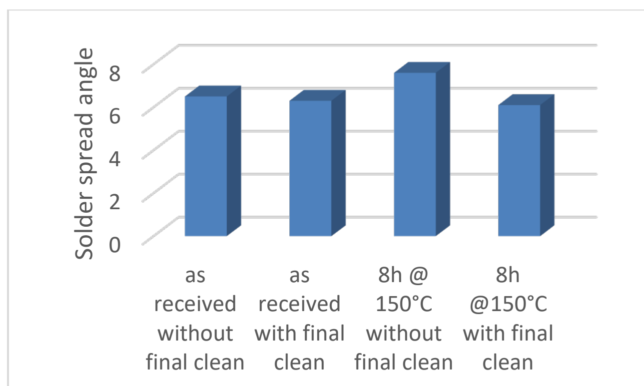

Figure 8: impact of final clean on solder spread results

SUMMARY AND CONCLUSION

In this study the properties of the gold layer in an ENIG finish were investigated and correlated to the gold layer thickness. It was shown, that with a low thickness of gold the formation of the layer is overall even but consists of small crystals. Only with increasing thickness a dense layer is formed with homogeneous coverage of the nickel surface. Electrochemical measurements confirm that at lower thickness the gold layer exhibits a porosity which does not fully protects the nickel from the corrosive attack of the measurement electrolyte. This also enable the migration of nickel and nickel oxides to the surface leading to a lower wettability in the soldering process. This can be correlated to the enrichment of nickel oxides at the ENIG surface as confirmed with EDX measurements after thermal aging. To ensure a sufficient solderability and to mitigate the risk of nickel migration to the surface, the gold layer thickness needs to follow the minimum requirements as defined in the IPC 4552.

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