

EMI Shielding by Plating Technique and Its Performance on the Shielding Effectiveness

Tai, Min Fee, Kok, Swee Leong, Kenichiroh Mukai

Abstract: In the effort to miniaturize the electronic packaging, plating on mold compound has been intensively studied as a solution to replace the metal can for Electro-Magnetic Interference (EMI) shielding. Plating technique is capable to reduce 5 to 10 times space compare to the metal can. A pre-shielded package can be done by plating in an array form before send to the die cut. This will enable shielding in bulk hence reduce the manufacturing foot print and cost. In our past research work, we had demonstrated a feasible manufacturing process, and the plated product had reached the high reliable performance [1]. Following the research, we design a series of microstrip patch antennas to evaluate the effectiveness of EMI shielding by the plating technique, in frequency of 2.65, 6.26 and 10.0GHz. Antennas are coated with conformal coat ink as the insulator, followed by plating of the nickel-phosphorous (NiP) and the pure copper (Cu). The capability of plated metal shield to attenuate the antenna receiving power, is used to evaluate the performance of EMI shielding effectiveness (SE). Result showed a direct co-relation of the metal thickness towards EMI shielding effectiveness, but it come into saturation when we further increase the thicknesses. Besides, test also shown material selection on copper versus nickel-phosphorous with its high differences on conductivity and permeability properties, resulting in different EMI shielding performance at different frequency. The combination of 2 different metal metals enhance the EMI shielding result compare to single metal.

KEYWORDS: EMI shielding, shielding effectiveness, antenna, nickel plating, copper plating.

I. INTRODUCTION

The overcrowding of wireless signal in surrounding had led to EMI shielding becoming more important. According to industry news, Apple is applying EMI shield technology to variety of digital chips, radio frequency, connectivity (wireless LAN, Bluetooth) chips and others that also include application processor and modems. It is a measure to increase device's performance while decreasing electromagnetic interference to major chips and to solve people's fear on electromagnetic waves from smartphones [2].

When electronic devices receive strong electromagnetic waves, unwanted electric currents can be induced in the circuit and thus cause unintended operations or interference with the intended operations. If the energy

Revised Manuscript Received on October 22, 2019.

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applied from the outside is too powerful, electronic devices can be damaged. Even if the energy applied from the outside is small, if it is mixed with the radio waves used for broadcasting and communication, it can cause loss of reception, abnormal noise in sound, or disrupted video at places where the radio waves for broadcasting and communication are weak. Such interference caused by external electromagnetic waves is called electromagnetic noise interference, and the electromagnetic waves that cause interference are called electromagnetic noise. Noise can cause interference with various electronic devices. The source of noise also varies. Noise that does not cause any interference with particular appliances (e.g. washing machines and refrigerators) but can seriously affect other devices (e.g. AM radios). Therefore, there are rules to suppress the noise generated from electronic devices to a certain level and to make sure that electronic devices operate correctly under a certain noise level so that we can use electronic devices with security. These rules are called noise regulations. If an electronic device is considered a source of noise, the occurrence of noise is called emission of noise. In contrast, if an electronic device is considered a victim of noise, the tolerance to noise is called immunity (noise tolerance). Noise regulations specify the emission and immunity of electronic devices. [3]

II. 2.0. EMI SHIELDING FABRICATION TECHNIQUE

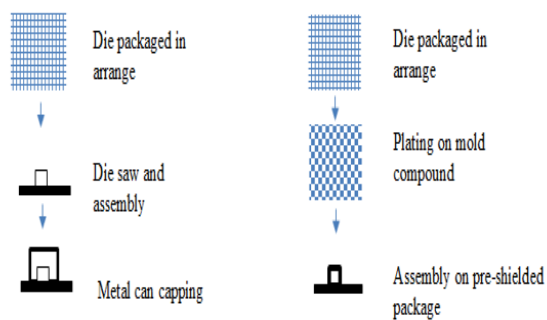
Alternative methods of EMI shielding are actively researched nowadays in the electronic industry [4]. The reasons are to fulfil the change of the challenging demand such as multifunctioning in a single device, which all chips need to be electromagnetically contained so it will not interfere others or being interfered during the operation. To substitute the metal can, a conformal coated metal on package (mainly on the outer layer of the mold compound) can help to save space up to few hundred micrometre, which is significantly in the electronic world. Conformal techniques which are currently available are screen-print, metal spray, sputtering and plating. The traditional old technique of screen printing has limitation on higher density design due to its thickness is high and very poor coverage on side wall [5].

The ability to coat on 3 dimension structures needs a high throwing power capability. In thin film metal coating, plating and Physical Vapor Deposition (PVD) are the preferred selection due to its well thickness control in thin layer and uniform.

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There is a problem about the layer formation by present technology uses Chemical vapor Deposition (CVD) or Physical Vapor Deposition (PVD, also known as sputtering) which needs high vacuum and with the equipment of high cost. In the case of sputtering, it is difficult to form a conformal film in a high aspect ratio structure. Improvements have so far been made by achieving required film thickness when depositing seed layers within high aspect ratio via and at via bottoms by using long-term process; but it in addition prolonged the process time, such measure increases cost and lowers productivity. On the other hand, CVD needs high temperature process which affects the device performance. Despite the advances that have recently been made to improve the process of thin film barrier deposition by atomic layer deposition (ALD), issues remain in the development of advanced techniques for seed layers. Plating have advantages among others on low cost, thin layer control, good throwing power on dead corner coverage. Meanwhile the drawbacks plating is the environmentally challenge and backside coating is needed to cover the not-to-plated area [6].

Figure 1 illustrates the conventional versus new approach on EMI shielding by plating. Traditional EMI shielding by metal can is done on the last step after chip assembly. This method takes extra cost and it consumes more height and space. Means while by using plating on array form, shielding can be done on high volume scale, and reduce the size of package. During design on experiment, we put cost effective and ease of industrial mass production as factor of consideration. Electroless NiP is chosen due to it fast deposition, low running cost, and its high wear and corrosion resistance, which it can stand as the final finishing layer of the product. Besides, copper is also a cheap and easy available material. Copper has high conductivity and give high skin depth while handling the high frequency electro-magnetic wave.



a. New EMI Shielding by plating

by metal can

Figure 1: Conventional vs New Approach of EMI shielding

III. MEASURING OF EMI SHIELDING EFFECTIVENESS

In summary, the shielding effectiveness in dB, SE_{dB} is,

$$SE_{dB} = R_{dB} + A_{dB} + M_{dB} \quad (1)$$

where R_{dB} is the reflection loss, A_{dB} is the absorption loss, and M_{dB} is the multi-reflection loss. Equation is further explained by Figure 2. Due to the fact that the wave is attenuated to $1/e$ at one skin depth, the multi-reflection loss

can be ignored for the cases where the shielding thickness is much larger than the skin depth.

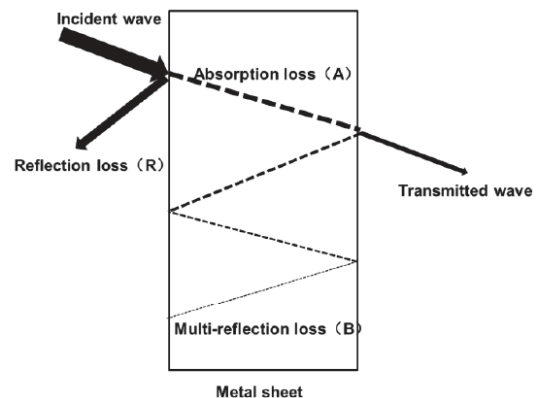


Figure 2: Electromagnetic Shielding Schematic Diagram [7]

The reflection loss is

$$R = 20 \log_{10} \left| \frac{(Z_0 + Z_1)^2}{4Z_0 Z_1} \right| \quad (2)$$

where Z_0 represents the wave impedance of air and Z_1 represents the wave impedance of the metal sheet. As

$$Z_1 \approx \sqrt{\frac{\mu_1 \omega}{\sigma_1}} (1 + j) \ll Z_0 = 120\pi \omega \quad (3)$$

μ_1 and σ_1 are the relative permeability and conductivity of the metal sheet, respectively, formula (3) can be estimated as

$$R = 20 \log_{10} \left| \frac{Z_0}{4Z_1} \right| = 20 \log_{10} \left| \frac{30\pi}{1+j} \sqrt{\frac{\sigma_1}{\mu_1 \omega}} \right| \quad (4)$$

The reflection loss is directly proportional to the conductivity of the metal sheet but inversely proportional to the relative permeability of the metal sheet.

The absorption loss is

$$A = 20 \log_{10} e^{\frac{L}{\delta}} \quad (5)$$

where L is the thickness of the metal sheet and δ is the skin depth.

b. Conventional EMI shielding $\delta = \sqrt{\frac{2}{\mu_1 \omega \sigma_1}}$ (6)

Formula (5) can be estimated as

$$A = 20 \log_{10} e^{\sqrt{\frac{\mu_1 \omega \sigma_1}{2}} L} \quad (7)$$

The absorption loss is directly proportional to the thickness, conductivity and relative permeability of the metal sheet.

The multi-reflection loss is

$$B = 20 \log_{10} \left| 1 - \frac{(Z_0 - Z_1)^2}{(Z_0 + Z_1)^2} e^{-2(1+j)\frac{L}{\delta}} \right| \quad (8)$$

As $Z \gg Z_1$, formula (8) can be estimated as

$$B = 20 \log_{10} \left| 1 - e^{-2(1+j)\frac{L}{\delta}} \right| \quad (9)$$

If the thickness of the metal sheet is much larger than skin depth, incident wave will be attenuated significantly so that the multi-reflection loss will be negligible.

The EM shielding capability of a shield is described as shielding effectiveness, SE , which is defined as the ratio of the electric fields and magnetic field at a point without and with the shield as equation 10a and 10b,

$$SE = 20 \log_{10} \frac{E_1}{E_0} \quad (10a)$$

$$SE = 20 \log_{10} \frac{H_1}{H_0} \quad (10b)$$

where E_1, H_1 is the electrical and magnetic field at an arbitrary point without the shield, and E_2, H_2 is the electrical and magnetic field at the same point with the shield [7].

As power is quadratic of electrical and magnetic force, the equation can be further elaborated into

$$SE = 10 \log_{10} \left(\frac{P_1}{P_2} \right), \text{ for power unit in watt} \quad (11)$$

$$S_E = 10 \log_{10} P_1 - 10 \log_{10} P_2 \quad (12)$$

$$S_E (\text{in dB}) = P_1 - P_2 \quad (13)$$

for power unit in dBm

From table 1, we notice different material will have various physical characteristic on conductivity and permeability, which causing selection of material is important to determine the shielding effective of design.

Table 1: Electrical conductivity relative to copper (σ_r) and relative magnetic permeability (μ_r) of selected material. [8]

Material	σ_r	μ_r	$\sigma_r \mu_r$	σ_r / μ_r
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Brass	0.26	1	0.26	0.26
Bronze	0.18	1	0.18	0.18
Tin	0.15	1	0.15	0.15
Lead	0.08	1	0.08	0.08
Nickel	0.2	100	20	2×10^{-3}
Stainless steel (430)	0.02	500	10	4×10^{-5}
Mumetal				
(at 1 kHz)	0.03	20,000	600	1.5×10^{-4}
Superpermalloy				
(at 1 kHz)	0.03	100,000	3,000	3×10^{-7}

In the electroless NiP plating, by increasing of Phosphorous (P) content is a common method to improve the corrosion resistivity, but the electrical resistivity will also increase to double on after 11% P (in weigh %) versus the pure nickel.

Effect of EN deposit composition on electrical resistivity

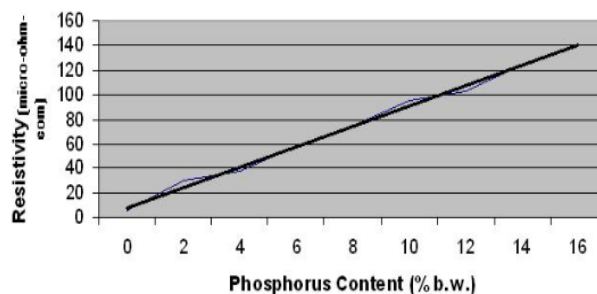


Figure 3: Effect of Resistivity vs Phosphorous content

IV. EXPERIMENTAL SET-UP

3 microstrip patch antennas are designed to test the reacceptance of signal at 2.75 GHz, 6.26GHz and 10.0 GHz as shown in Figure 4. Selection of frequency are meet to current 4G bandwidth, and extend to higher frequency for future 5G expansion need. The antennas are fabricated on FR4 substrate with permittivity and thickness of 5.4 and 1.6 mm respectively. The substrate has copper thickness of 0.035 mm at both sides. In this design, quarter-wave matching approach is used to get bigger bandwidth. The antenna is fed with 50 Ω SMA using the edge feeding technique.

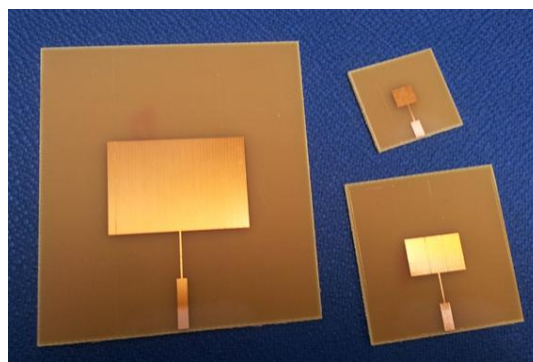
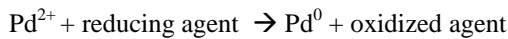


Figure 4: Fabrication of Antenna

Sample fabrication begins with copper clad laminating with FR4 dielectric. Antenna pattern is formed by printing of etch resist on copper clad; the unwanted Cu is removed with cupric chloride etchant. When the pattern is formed, the etch resist is stripped and exposed the pattern in Cu. The fabrication process is then followed by using conformal coating ink to cover the antenna, to act as an insulator to antenna layer. A series of antenna samples are dried for 2 days to ensure the ink are fully dried and cured. After that the samples are ready for the metal plating process.

As conformal coating ink is not conductive, therefore surface activation is needed; this is begun with palladium colloid to form a seed layer prior to plating. This is done by the catalytic metallic nuclei of metal Palladium on the non-catalytic surface; by generating an electrochemical oxidation–reduction reaction,

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where Pd^{2+} is the metallic ion and Pd^0 is the metal catalyst. In many case the preferred reducing agent is Sn^{2+} , which would be oxidized into Sn^{4+} .

The fabrication process is followed by electroless plating of nickel-phosphorous (NiP). NiP is a preferred process due to its low cost and the throwing power is essentially perfect. Metallization of NiP is an autocatalytic deposition of ion Ni^{2+} reduced by sodium hypophosphate [9].



Table 2: Bath Components for NiP Electroless Plating [9]

Chemical	Concentration
$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$	40–50 g/l
$\text{NaH}_2\text{PO}_2 \cdot \text{H}_2\text{O}$	30–40 g/l
NH_4Cl	60–80 g/l
$\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$	40–50 g/l
$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	10–20 g/l

After plating a layer of NiP, the test is then carry on with additional deposition of copper (Cu) with thicknesses 3,5, and 10um on top of conductive layer 20um NiP. As electroless Cu deposition rate is very slow and costly, process selection switch to electrolytic Cu. The sample is connected in a Cu plating bath where the sample itself is acting as the cathode (negative charge), and another Cu bar as the anode (positive source) and the electrolyte is made up of acidic copper sulphate solution. The setup of the experiment is shown in Figure 5, when the rectifier is turned on, copper starts to deposit from anode to cathode.

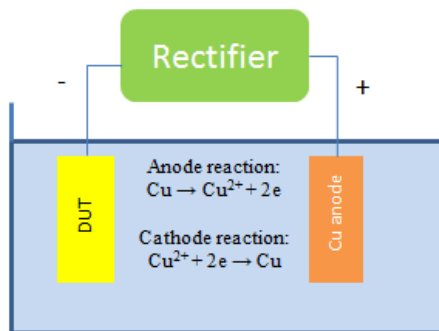


Figure 5: Electrolytic Plating on Copper

Table 3: Bath Component for Acid Copper Solutions [10]

Chemical reagents	Concentration
Copper sulphate, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	200–250 g/l
Sulfuric acid, H_2SO_4	60–100 g/l
Chloride	40–80 mg/l
Leveller	20–30 g/l
Brightener	0.5–1.5 g/l

The overall processes of sample preparation are illustrated by Figure 6.

Step	Top View	Side View
1		
3 types of antenna designed with different size with Copper print and etch technique		
2		
Contact point is covered by Kapton tape		
3		
Print conformal coat ink on antenna circuit to insulate the area		
4		
Activate the surface of conformal coat with Palladium, follow by plating of Electroless Ni.		
5		
Remove the Kapton tape, measure the shielding effectiveness of nickel layer.		
6		

Repeat test with additional electrolytic copper plating

Figure 6: Process Flow of DUT Preparation

The measuring of EMI shielding effectiveness is based on the attenuation of antenna after shielded by metal. Devices under test (DUT) are place on connection to signal analyser, facing to horn of signal generator, with distance of 50cm. The signal generator is tune to 2.75 Hz, 6.26 Hz, and 10.0 Hz to match the acceptance signal of antenna; with power of 20dBm. The powers received by antenna are recorded by signal analyser, and data is used for SE calculation (Figure 7).

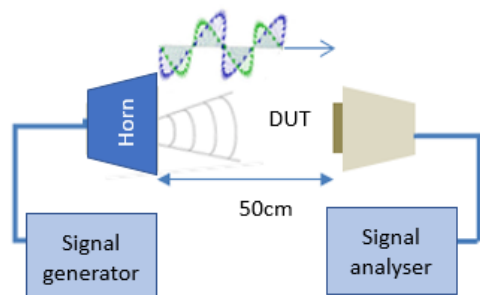


Figure 7: Measuring of Electromagnetic Shielding Effective

V. EXPERIMENT RESULTS & DISCUSSION

In principle, the plated metal (NiP or Cu) will act as the shielding layer to absorb and to reflex the electromagnetic wave from the horn transmitter. The minimum power receiving from the antenna is indicating the better EMI shielding performance.

Design of experiment starts with microstrip patch antennas, the NiP plated samples with thickness of 1, 3, 5, 10, 20, 30 are tested at 2.75, 6.26 and 10.0 GHz. Antennas are placed as DUT shown in Figure 7, facing oppositely to a horn which impose noise with various of frequency, in fixed energy 20 dBm. The signal analyzer which connected to the DUT will measure the energy received after attenuated by the plated metal. The differences of energy received between metal-shielded and non-metal-shielded is used to study the EMI shielding efficiency (Figure 8).

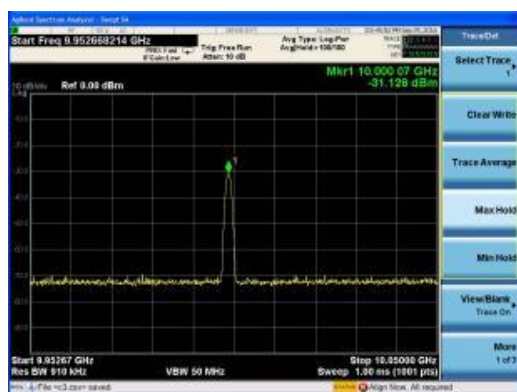


Figure 8: Raw Data on Measuring EMI Shielding Efficiency by Signal Analyzer

From the first result in Figure 9, we see the SE is steadily improved over the increase of NiP thickness, but its reach the limitation after 10-20um thicknesses. For frequency of

2.75Hz, a SE of above 17dB is achievable with more than 20um of NiP; mean whiles, for 6.25GHz, maximum SE of 10dB is recorded after 20um. It is also found that lower frequency signal (2.75GHz) is easier to shield compare to the higher frequency (6.26, 10 GHz) by NiP material. In noise frequency of 10GHz, the shielding efficiency show only around 3dB even 20-30um of NiP is applied.

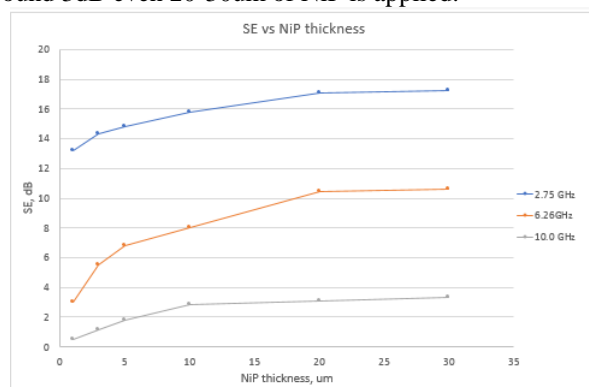


Figure 9: Shielding Effectiveness vs Nickel-Phosphorous Thickness

From the Equation 5, the absorption loss is

$$A = 20 \log_{10} e^{\frac{L}{\delta}} \quad (5)$$

where L is the thickness of the metal sheet. When the thickness of NiP increase (L increase), the absorption loss towards external noise will increase, hence higher metal thickness gives better SE until it is limited by others factor such as skin effect.

In order to extend the shielding effectiveness, a different material, Copper (Cu) is plated on top of 20um NiP surface.

The NiP 20um and Cu plated samples with thickness of 1, 5, 10 are tested at 2.75, 6.26 and 10.0 GHz.

On the additional Cu plated on top of 20um NiP, we see Cu is capable improving the SE. On 2.75 GHz, the SE increase to 20 dB, whereby the 6,26GHz increase into 14dB, and 10GHz increase to 9dB. In general, increasing the Cu thickness after 5um shows its limitation to further improve the SE.

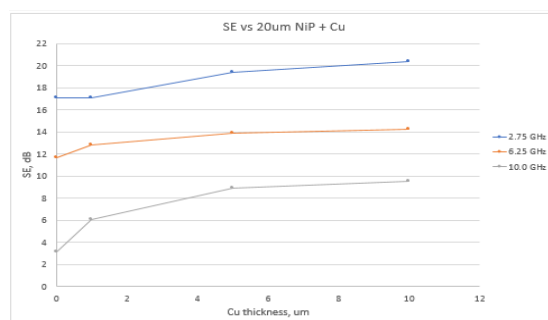


Figure 10: Further Improvement of SE with additional Cu plated on top of 20um NiP.

From the Figure 10 test result, we also notice Cu give better SE capability vs NiP. Cu has better relative conductivity 1.0, which is 5 times than pure Ni (Table 1). Increasing the phosphorus content will further increases the electrical resistivity of the film.

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NiP at around 8% of Phosphorous will have 10 times lower conductivity than pure Ni (Figure 3.) From the Equation 7 and 8, the reflection loss and absorption loss is proportional to the conductivity. Cu with higher conductivity gives better reflection loss and absorption loss capability, which indicate its higher EMI shielding capability.

Additional Cu in high frequency 10.0GHz show SE increase from 3dB into 9dB, which is almost 200% of the improvement. Electromagnetic radiation from the high frequency penetrates only at the near surface region of conductor layer, which normally called skin effect. Most materials have the relative permeability μ_r at near to 1, including copper. The exceptions are nickel, iron, etc, which are called ferro-magnetic materials. Metals such as nickel can have permeability as high as 100 or more.

From equation 6, the skin depth, δ , note it is dominated by the conductivity, μ and permeability, σ . For copper, when relative conductivity, $\mu_r = 1$, and $\sigma_r = 1$, $\delta_r = 44.7 \times 10^{-6}$ at 10.0 GHz; and for nickel, when relative conductivity, $\mu_r = 0.2$, and $\sigma_r = 100$, $\delta_r = 3.16 \times 10^{-6}$ at 10.0 GHz. Ni is 5 times lower conductivity than Cu, but the ultimate conductivity of a nickel thin film can be as low 7% compare to Cu. This is because the skin depths are much thinner due to the relative permeability term, which is often reported at 100 for nickel. Permeability is a strong function of frequency once we reach few GHz. The magnetic domains can't follow the fast-changing magnetic field anymore and relative permeability drops down towards unity. Permeability and frequency are both in the denominator of the skin-depth formula [11].

Nevertheless, NiP is still a prefer layer in combination to Cu in designing of plating solution of EMI shielding. NiP with its ferromagnetic characteristic, the shielding at very lower frequency (lower than 10MHz) could be significant. Besides, NiP with its good corrosion resistance and high hardness can protect the Cu layer from oxidation and the mechanical damage. Such combination compensates the weaknesses on each material and form the perfect match.

VI. CONCLUSION

With the combination with plated NiP and Cu, a range of 9-20 dB shielding effectiveness can be achieved. NiP to combined with Cu is a better EMI shield compared to NiP alone. SE does not increase with metal thickness. Saturation of performance found at thickness of 20um NiP and 5 um Cu, beyond this it come to flat. Selection of thickness and material will depend on the EMI shielding design requirement and the target cost. 3 of the EM frequencies have shown same pattern of changes although the SE is better at lower frequency. The conformal plating on mold compound provides alternative solution for EMI shielding in IC packaging.

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