“A Study on the Electrical Characteristics of Different Wire Materials”

by

Chi-Hyeon Jeong, Billy Ahn, Coronado Ray, Liu Kai, Ma Phoo Pwint Hlaing, Susan Park and Gwang Kim*
STATS ChipPAC Inc, Korea,
Bubal-eub Icheon-si Kyoungki-do,
467-701, Korea

A Study on the Electrical Characteristics of Different Wire Materials

Chi-Hyeon Jeong, Billy Ahn, Coronado Ray, Liu Kai, Ma Phoo Pwint Hlaing, Susan Park and Gwang Kim*

STATS ChipPAC Inc, Korea, Bubal-eub Icheon-si Kyoungki-do, 467-701, Korea

Abstract Gold wire has long been used as a proven method of connecting a silicon die to a substrate in wide variety of package types, delivering high yield and productivity. However, with the high price of gold, the semiconductor packaging industry has been implementing an alternate wire material. These materials may include silver (Ag) or copper (Cu) alloys as an alternative to save material cost and maintain electrical performance. This paper will analyze and compare the electrical characteristics of several wire types. For the study, typical 0.6 mil, 0.8 mil and 1.0 mil diameter wires were selected from various alloy types (2N gold, Palladium (Pd) coated/doped copper, 88% and 96% silver) as well as respective pure metallic wires for comparison. Each wire model was validated by comparing it to electromagnetic simulation results and measurement data. Measurements from the implemented test boards were done using a vector network analyzer (VNA) and probe station set-up. The test board layout consisted of three parts: 1. Analysis of the diameter, length and material characteristic of each wire; 2. Comparison between a microstrip line and the wire to microstrip line transition; and 3. Analysis of the wire's cross-talk. These areas will be discussed in detail along with all the extracted results from each type the wire.

Keywords: BONDING, COPPER, GOLD, MATERIAL, SILVER, WIRE
* **Corresponding Author email: gwang.kim@statschippac.com**

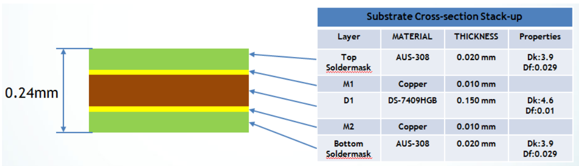
1. INTRODUCTION

Wire bonding is the method of making interconnections between the silicon chip and substrate. With the high price of gold, the semiconductor packaging industry is increasingly implementing alternative wire materials. These materials may include silver alloy or copper wires as alternatives to save material cost and maintain electrical performance. This study is focused on the electrical performance of each wire material. In the case of low operating frequency devices, the most important properties of wire bonding are physical reliability and bondability. In the past, the wire electrical characteristic has not had a significant impact on signal quality due to the relatively low data rate. However, recent advances in semiconductor industry, with respect to increased operating frequencies for bonding wires has caused the data rate to be faster than previous devices. Therefore, wire materials also need to be evaluated on the transmission behaviors for signal integrity and power integrity. The bonding wire on mold material which is used as an interconnect in high frequency operations causes a high characteristic impedance, which results in mismatched circuit and high signal reflection. In addition, radiation loss due to discontinuity is caused by the wire edge structure. [1]-[3] To begin with, each of the wire materials has a known resistivity or conductivity value which has been proven by other studies. [4]-[8] However, a comparison of the following wire materials: Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu have not been discussed in detail. This paper focuses on the electrical characteristics of each wire. A variety of bonding wires with different characteristics in terms of diameter, material and frequencies were simulated and measured. Additionally, a comparison between a microstrip line and the wire to microstrip line transition structure is presented, and the cross-talk between two wires with 0.5 mm separation was analyzed. In addition, simulation and measurement results of each wire are overlapped for easy comparison.

2. MODELING AND SIMULATION

In this study, bond wire modeling is based on results of electromagnetic simulation performed using a HFSS v.

15. The substrate core of the model is DS-7409HGB, with the thickness of 0.150 mm. The relative core permittivity is 4.6 and prepreg permittivity is 3.9. The thickness of the top metal layer and bottom metal layer on the substrate is 0.01 mm. The thickness of the top and bottom solder mask layer is 0.02 mm. Thus, total thickness is 0.24 mm. The substrate cross section is shown in Fig. 1.



Substrate Cross-section Stack-up			
Layer	MATERIAL	THICKNESS	Properties
Top Soldermask	AUS-308	0.020 mm	Dk:3.9 Df:0.029
M1	Copper	0.010 mm	
D1	DS-7409HGB	0.150 mm	Dk:4.6 Df:0.01
M2	Copper	0.010 mm	
Bottom Soldermask	AUS-308	0.020 mm	Dk:3.9 Df:0.029

Fig. 1. Cross section of substrate

The present modeling scheme is summarized in Fig. 2. After 3D wire geometry is entered into EM, a simulation is performed to generate two-port or four-port S-parameters. The simulation frequency ranges from 0.5 GHz to 40 GHz. For the wire bond configurations, different diameters and lengths are selected. In order to compare composition material and pure material, the materials of three wire types were set to pure. For the simulation, we performed a case study using three different wire materials (Pure Au, Pure Ag, Pure Cu). To compare the each wire, S-parameters were extracted from the layout as shown in sections 1, 2 and 3. Multiple curves of all tested wire results are included in each figure. Loop wire is 0.1 mm above the top metal.

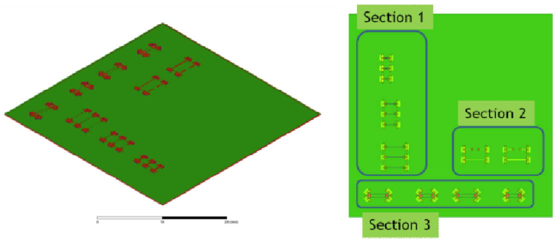


Fig. 2. Cross section of substrate

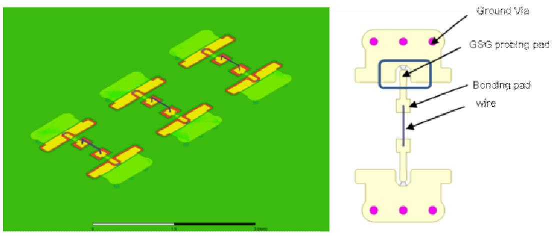


Fig. 3. Structure of Section 1 and probing pad

Table 1. Test matrix of experiment

	Wire type	Wire diameter	Wire length	Total # of legs
Section 1	Au(2N) Pd Coated Cu Silver (96%) Silver (88%) Pd dopped Cu	0.6 mil 0.8 mil 1.0 mil	0.5 mm 1.5 mm 3.0 mm	45 leg
	Wire type	Wire diameter	Trace width	Total # of legs
Section 2	Au(2N) Pd Coated Cu Silver (96%) Silver (88%) Pd dopped Cu	0.8 mil	0.1mm 0.2 mm	10 leg
	Wire type	Wire diameter	Wire length	Total # of legs
Section 3	Au(2N) Pd Coated Cu Silver (96%) Silver (88%) Pd dopped Cu	0.8 mil 1.0 mil	2.0 mm 3.0 mm	20 leg

In Section 1, the wire-bond performance was investigated as a function of diameter, length and material. Test structures with different lengths (500 µm, 1000 µm, 1500 µm), diameters (0.6 mil, 0.8 mil, 1.0 mil), and materials were fabricated. For each configuration, 27 models were simulated from 0.5 GHz to 40 GHz. Extracted S-parameter was converted into a Z-parameter, and the Z-parameter was converted into inductance values for evaluation. Table 2 provides the electrical parameters for the wire inductance. It is clear that as the wire diameter increases, the inductance decreases. The wire length and frequency are another critical factor that affects the inductance value. The wire length varies from 500, 1500, and 3000 µm. At 500 µm, the inductance is not sensitive. However, at 1500 µm and between 5 GHz and 10 GHz, inductance rapidly increases.

Table 2. Simulation results of Section 1 (Unit : nH)

Frequency	1GHz								
Length (µm)	500			1500			3000		
Diameter (mil)	0.6	0.8	1	0.6	0.8	1	0.6	0.8	1
Ag	1.08	1.03	1.00	1.94	1.83	1.76	3.19	3.05	2.92
Au	1.08	1.04	1.01	1.93	1.84	1.78	3.18	3.05	2.94
Cu	1.08	1.04	1.01	1.94	1.84	1.77	3.20	3.06	2.93
Frequency	5GHz								
Ag	1.11	1.06	1.04	2.12	1.99	1.91	3.93	3.71	3.54
Au	1.12	1.07	1.04	2.11	1.99	1.93	3.91	3.72	3.55
Cu	1.11	1.07	1.04	2.11	1.99	1.92	3.94	3.73	3.55
Frequency	10GHz								
Ag	1.29	1.23	1.20	3.21	2.95	2.79	21.63	16.58	13.86
Au	1.30	1.24	1.20	3.20	2.95	2.83	21.25	17.41	13.95
Cu	1.29	1.24	1.20	3.20	2.96	2.80	21.42	16.85	13.78

For Section 2 structures, some transmission testers which are critical for system performance were investigated. The wire to microstrip line transition structure can have high characteristic impedance. Discontinuity of the transmission line can interfere with the signal flow. The insertion loss and reflection coefficient are sensitive to the transmission structure. Transmission line was investigated as a function of line width and material. Test structures were fabricated with different trace widths (0.1 mm, 0.2 mm) and materials. Fig. 5 and 6 provide the simulation results.

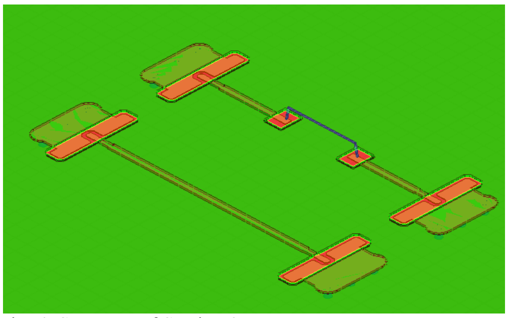


Fig. 4. Structure of Section 2

Figures 5 and 6 show the simulated magnitude (Pure Cu, Pure Ag, Pure Au) of S11 and S21 of the microstrip line and transition structure. As indicated in Figures 5 and 6, the return loss of trace is better than transition structures.

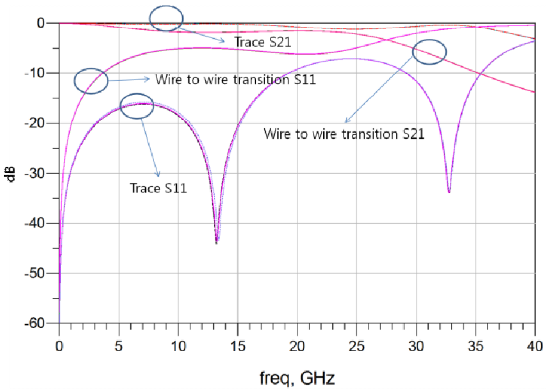


Fig. 5. Simulation results of wire to wire transition and microstrip line (trace width 0.2 mm with Pure Cu, Pure Ag and Pure Au)

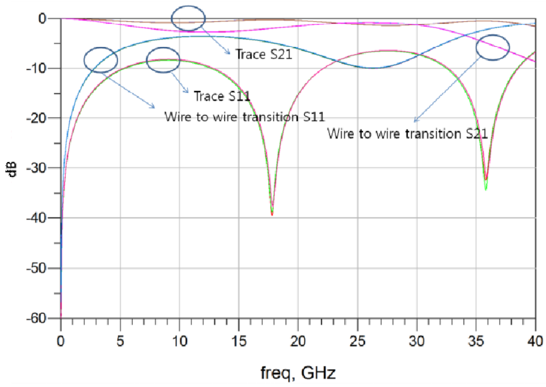


Fig. 6. Simulation results of wire to wire transition and microstrip line (trace width 0.1mm with Pure Cu, Pure Ag and Pure Au)

Through Section 3 structures, the cross-talk problem was investigated. A critical factor of cross-talk is wire to wire distance. However, due to the fabrication limit of the substrate probing structure, the minimum distance from wire to wire was 0.5 mm. Therefore, the wire to wire distances were all set to 0.5 mm. Thus, the experiments focused on the diameter and material. The test model shown in Fig. 7 consists of two adjacent wires with different diameters, lengths and materials. Figures 8, 9, 10 and 11 show the results of cross-talk.

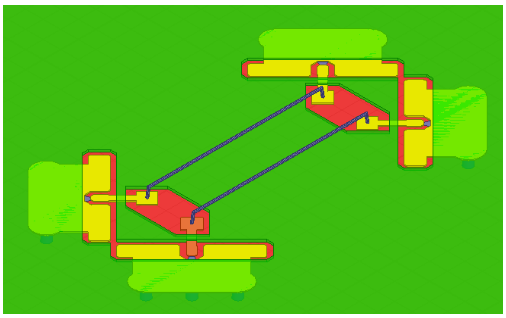


Fig. 7. Structure of Section 3

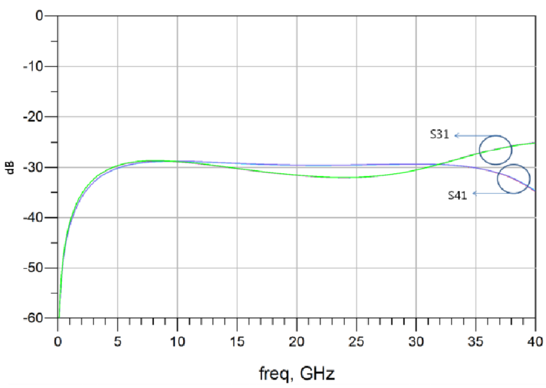


Fig. 8. Cross-talk simulation results (0.8 mil diameter and 2000 μm wire length with Pure Cu, Pure Ag and Pure Au)

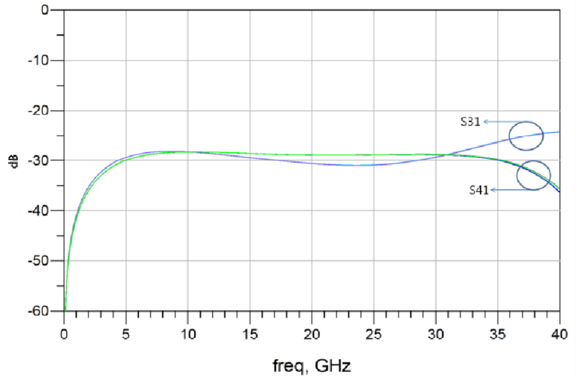


Fig. 9. Cross-talk simulation results (1.0 mil diameter and 2000 µm wire length with Pure Cu, Pure Ag, Pure Au)

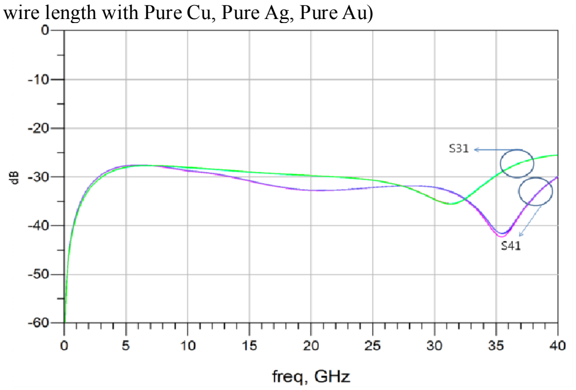


Fig. 10. Cross-talk simulation results (0.8 mil diameter and 3000 µm wire length with Pure Cu, Pure Ag and Pure Au)

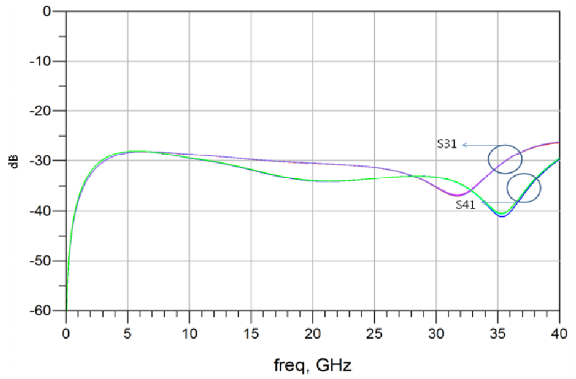


Fig. 11. Cross-talk simulation results with different wire materials (1.0mil diameter and 3000 µm wire length with Pure Cu, Pure Ag and Pure Au)

3. MEASUREMENT RESULTS

As mentioned before, a wire bonded substrate was implemented. From the measurement of implemented substrate, S-parameters were obtained by VNA. The measurement environment and implemented substrate are shown in Fig. 12.

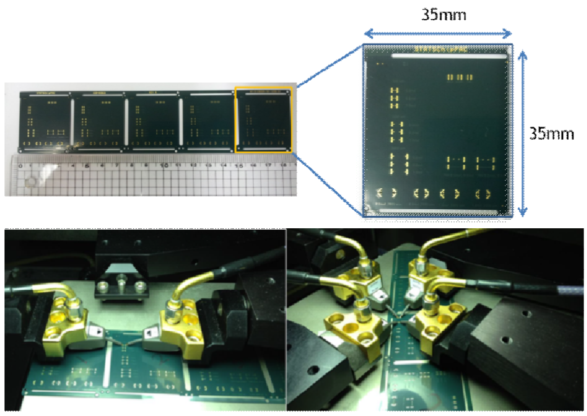


Fig. 12 Measurement environment and implemented substrate

For section 1 structures, measurement results are shown in Table 3. Wires of different lengths and diameters were measured to observe the effect on overall inductance values at different frequencies. The short, thick wires had low inductance values as expected. In addition, there was no significant difference in the values of inductance between the wires of different materials.

Table 3. Measurement results of Section 1 (Unit : nH)

Frequency	1GHz								
Length (µm)	500			1500			3000		
Diameter (mil)	0.6	0.8	1	0.6	0.8	1	0.6	0.8	1
Ag88%	0.88	0.84	0.82	1.74	1.65	1.59	3.10	2.96	2.83
Ag96%	0.87	0.84	0.83	1.75	1.65	1.60	3.10	2.94	2.84
Au(2N)	0.86	0.83	0.80	1.71	1.61	1.54	3.01	2.88	2.75
Pd doped Cu	0.86	0.85	0.82	1.73	1.63	1.55	3.03	2.78	2.62
Pd Cu	0.86	0.84	0.82	1.72	1.64	1.57	3.04	2.89	2.76
Frequency	5GHz								
Ag88%	0.88	0.84	0.81	1.84	1.74	1.68	3.67	3.49	3.32
Ag96%	0.87	0.83	0.82	1.86	1.74	1.68	3.66	3.43	3.33
Au(2N)	0.86	0.83	0.80	1.81	1.71	1.63	3.56	3.40	3.21
Pd doped Cu	0.86	0.85	0.82	1.83	1.73	1.63	3.61	3.26	3.05
Pd Cu	0.87	0.85	0.82	1.83	1.74	1.66	3.64	3.43	3.26
Frequency	10GHz								
Ag88%	0.97	0.93	0.89	2.48	2.28	2.22	10.37	8.64	8.46
Ag96%	0.96	0.92	0.91	2.57	2.33	2.18	10.94	9.58	8.52
Au(2N)	0.95	0.91	0.88	2.42	2.23	2.13	9.39	8.40	7.25
Pd doped Cu	0.94	0.93	0.90	2.49	2.31	2.15	10.70	8.09	7.20
Pd Cu	0.95	0.93	0.90	2.51	2.34	2.20	11.37	9.76	8.51

Figures. 13, 14, 15 and 16 show the measured magnitude of S11 and S21 for Section 2 structures. These figures include present data for all test materials. The trace width 0.2 mm shows 3.03 dB and 3.27 dB ΔS21 for wire to wire transition structures at 10 GHz. On the other hand, the microstrip line shows 0.27 dB and 0.34 dB ΔS21 at the same frequency. The trace width 0.1 mm shows 1.02 dB and 1.10 dB ΔS21 for wire to wire transition structures at 10 GHz. On the other hand, the microstrip line shows 0.69 dB and 0.79 dB ΔS21 at the same frequency. Therefore, a large amount of insertion loss existed from the discontinuity of transmission line. It clearly indicates that microstrip line is better than wire to wire transmission line transition, especially for wider traces.

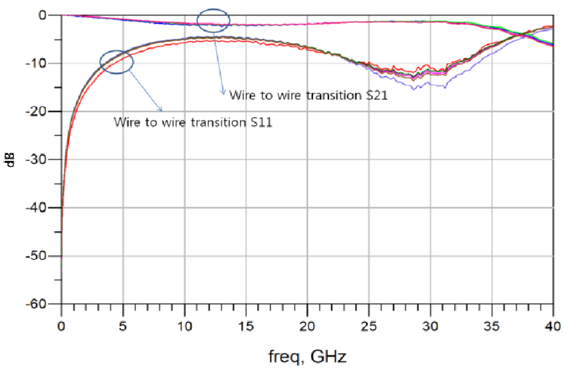


Fig. 13. Measurement results of wire to wire transition (trace width 0.2 mm with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

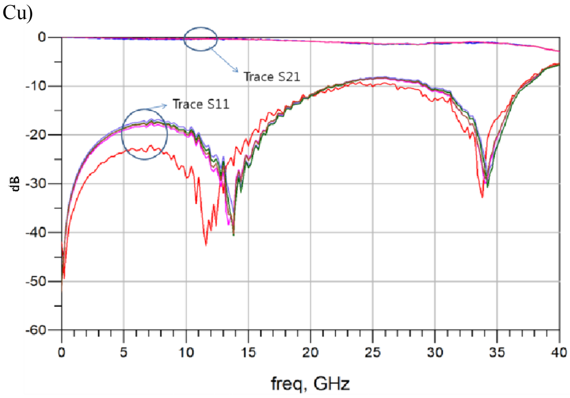


Fig. 14. Measurement results of microstrip line (trace width 0.2 mm with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

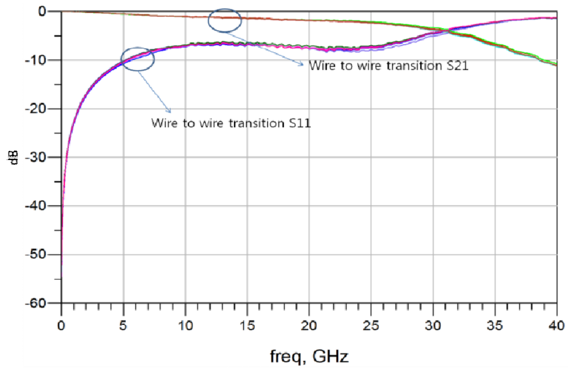


Fig. 15. Measurement results of wire to wire transition (trace width 0.1 mm with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

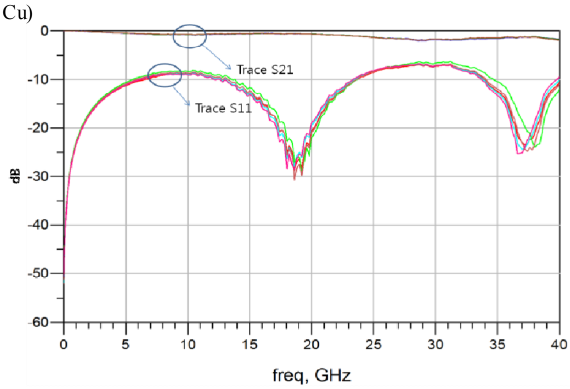


Fig. 16. Measurement results of microstrip line (trace width 0.1 mm with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

As mentioned earlier, Section 3 structures were used for the cross-talk study. Figures 17, 18, 19 and 20 provide the measurement results. It is necessary to compare each wire characteristic. The results illustrate the S-parameters of these cross-talk models. It was observed from the measured S41 and S31 curves that the cross-talk of these wire models were slightly different due to the variation of long wire sag. At a wire to wire distance of 0.5 mm, the cross-talk effect was not significant.

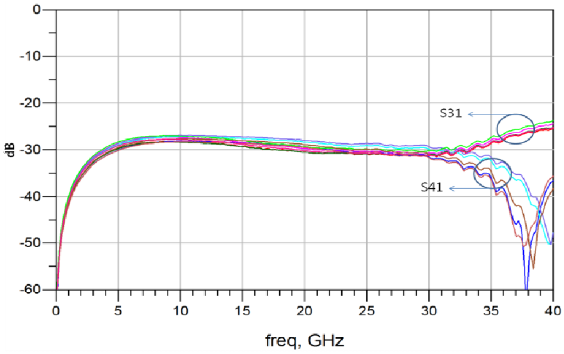


Fig. 17. Cross-talk measurement results with different wire materials (0.8mil diameter and 2000 μm wire length with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

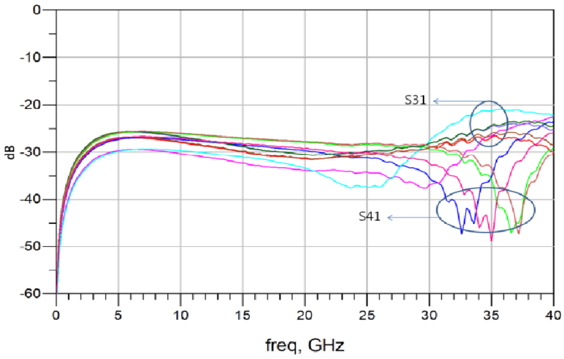


Fig. 18. Cross-talk measurement results with different wire materials (0.8mil diameter and 3000 μm wire length with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

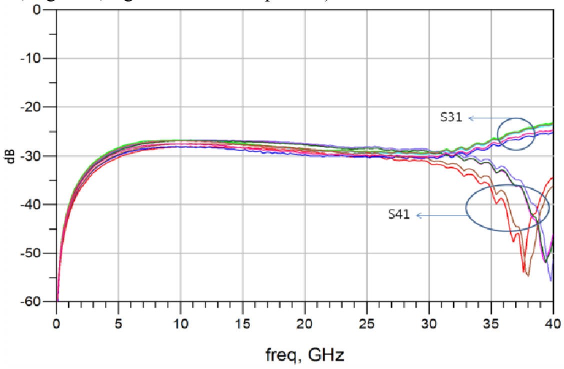


Fig. 19. Cross-talk measurement results with different wire materials (1.0mil diameter and 2000 μm wire length with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

4. CONCLUSIONS

This paper thoroughly investigates the performance variation of different materials, lengths and diameters of wires. Simulations have been conducted for each type of materials. The following conclusions can be drawn from the simulation and measurement results.

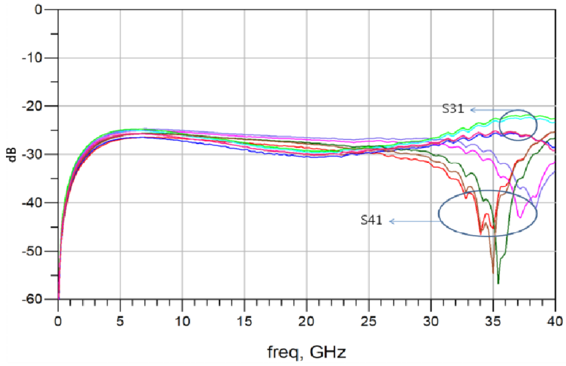


Fig. 20. Cross-talk measurement results with different wire materials (1.0mil diameter and 3000 μm wire length with Au(2N), Pd coated Cu, Ag 96%, Ag 88% and Pd doped Cu)

1. Inductance and S-parameter trends are almost the same among different wire materials.
2. When frequency is over 5 GHz and wire length is over 1.5mm, inductance rapidly increases.
3. Discontinuity of transmission line can interfere with the signal flow.
4. When the wire to wire distance is 0.5 mm, cross-talk of the wire is not sensitive to wire length and diameter.
5. Electrical responses are about the same from wires of different materials.

REFERENCES

(1) R. H. Caverly, IEEE Trans. on M.T.T 34, 982 (1986).
(2) Y. Kun, G. Wei, L. Zhihua and W. Lixi, 2011 12th International Conference on ICEPT-HDP p. 912, Shanghai, China (2011).
(3) H. Y. Lee, IEEE Trans. on M.T.T 43, 63 (1995).
(4) T. Ma, Y. Jiang, Y. Fan, X. Lin and Z. Zhu 2011 IEEE 4th International Symposium on MAPE, Beijing, China (2011).
(5) A. Sutono, G. Cafaro, J. Laskar and M. M. Tentzeris, IEEE Trans. on Advanced Packaging, 24, 595 (2001).
(6) K. Banerjee and A. Mehrotra, IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems, 21, 904 (2002).
(7) K. B. Unchwaniwala, and M. F. Caggiano, Proc. 51st Electronic Components and Technology Conference, p. 1496 Orlando, FL, USA (2001).
(8) S. Harkness, J. Meirhofer and B. J. Lameres, Electrical Performance of Electronic Packaging, p. 267, San Jose, CA, USA (2008).