

# Reliability of Transmission Lines Fabricated by Screen Printing for On-wafer Measurements at Millimeter-wave

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**Abstract**— The paper proposes new fabrication process for a planar circuits used at microwave and millimeter-wave frequencies. Screen printing technology is demonstrated to fabricate coplanar waveguides (CPW) lines as an impedance standard line for on-wafer device measurements at millimeter-wave frequency up to 110 GHz. The paper discusses the assessment of a screen printing technology in the characteristic of CPW lines fabricated on an alumina substrate usually adopted on an impedance standard substrate (ISS). CPW lines was printed by silver conductive ink and subsequent baking process by hot plate in the nitrogen gas flowing. Feature sizes with approximately 1.0  $\mu\text{m}$  tolerance for signal lines were realized successfully. The surface roughness of conductor was less than 0.5  $\mu\text{m}$ . Printed transmission lines provides insertion losses of 0.17 dB/mm at 60 GHz and 0.30 dB/mm at 110 GHz and it was better than plated CPW line being commercially available, i.e. 0.18 dB/mm at 60 GHz and 0.40 dB/mm at 110 GHz. Furthermore, return loss is almost the same as commercially available ISS, this means the transmission line patterns are almost high precision as same as commercial ISS fabricated by plating and etching. For contact reproducibility as important performance in the measurement process, printed conductors achieved more excellent reproducibility (N=10) than plated conductors, i.e. less than 0.02 dB for magnitude and less than 0.1 degrees for phase in short circuits.

**Keywords**— *Screen printing; On-wafer measurements; Impedance standard substrate; Scattering parameters; Contact reproducibility*

## I. INTRODUCTION

In recent years, the device electronics at millimeter-wave frequency is demanded in the telecommunication sector. For telecommunication device technology, applications require not only performance but also light weight, ultra-slim. In addition, cost efficiency is one of key factor to familiarize the product to the public.

Set of conductor plating, photolithography patterning and etching processes are commonly used in the traditional passive device fabrication and packaging. The fabrication is, thus, basically expensive and complex process. In addition, the process have to spend much time and produces waste fluid by the end of fabrication process. Recent interest in the electronic applications is driven by not only the low cost and environmental friendly, furthermore substrate material flexibility is demanded [1]-[5] from the mobile telecommunication and healthcare sectors.

Many laboratories have reported printing technology as solutions for microwave and millimeter-wave circuit fabrication. Some of reported research have achieved a loss of 2.8 dB/mm at 100 GHz [1], 0.27dB/mm at 20 GHz [2] and 0.35dB/mm at 110 GHz [6]. The printing technologies for microwave and millimeter-wave circuit fabrication processes are yearly getting better. However, almost the research employs an inkjet printing technologies in order to getting a fine resolutions suitable for millimeter-wave circuit fabrication processes. In the case of prototype circuit fabrication, use of inkjet printing technologies provide benefits, a lot of flexibility for circuit patterns and conductor thickness, etc., but it stands up poorly to high-volume productions due to low throughput process in general.

Screen printing technologies have to be a solution of circuit fabrication process for high-volume productions. The difficulties of adopting the screen printing process to microwave and millimeter-wave circuits are control and adjust of fabrication conditions, i.e. mesh count (resolution), paste characteristics and baking temperature, etc.. We have already successfully achieved fabrication process for DC electrical circuit applications made of conductor paste with very high-conductivity [7]. However, microwave and millimeter-wave circuits requires not only high-conductivity but also feature size, a cross sectional shape, surface roughness and adhesion of line, and ground conductors on a substrate.

In this paper, we use screen printing technologies to fabricate the coplanar waveguide (CPW) line structures. This paper describes, the first time, to demonstrate an implementation of screen printing technique to many sets of CPW lines and short circuits, as high-volume productions, on a substrate. The technique achieves over 260 CPW lines and short circuits with 1.0  $\mu\text{m}$  tolerance at the same printing routine. We used a design rule of single layered CPW line with 50  $\mu\text{m}$  width of signal line and 25  $\mu\text{m}$  width of gaps in order to comparing to conventional plated CPW line on impedance standard substrate (ISS) provided from Cascade Microtech. A thickness of metal conductor layer was initially 1.0  $\mu\text{m}$  as same as commercial product, Cascade Microtech 101-190 ISS. We report measurement results of dimensions results and scattering parameter (S-parameter) for CPW lines fabricated by screen printing technologies. Then, probe contact reliability, i.e. reproducibility, is evaluated and discussion in this paper.

## II. SAMPLE FABRICATION

### A. Fabrication Process

In the screen printing process, we used Screen Hand Printer ZT-320 provided from Process Service Co. Ltd.. Specification of screen mask with size of 320 mm x 320 mm used in the process are CAL-640 of mesh count providing 39% of open area. Line conductor was formed by silver paste, Daiken Chemical CA-T31, with contains 83 % silver and provides 310 Pa.s viscosity at 25 °C. Then low resistivity, typically  $1.86 \times 10^{-5} \Omega \cdot \text{cm}$ , can be formally achieved by baking at 150°C for 30 minutes.

In this paper, CPW lines were printed on an alumina substrate by screen hand printer and formed by baking at 150 °C and above (300 °C, 400 °C, 500 °C, 600 °C and 800 °C) for one hour in order to lower resistivity of conductors. 260 patterns of CPW lines (Figure 1) and short circuits were printed in the area of 29.0 mm x 20.5 mm. The printing process was operated under atmospheric conditions and subsequent baking process was carried out in nitrogen gas flow due to preventing the oxidation of silver ink as conductors.

For CPW at millimeter wave frequency, screen printing technology shall realize high conductivity, contact repeatability and small pattern with high resolution. Above mentioned process can produce high conductivity silver conductor, high adhesion characteristics and high resolution.

### B. Design of Coplaner Waveguide

CPW lines with ground plane was formed on a 254  $\mu\text{m}$  thick alumina substrate. The CPW line with ground plane are widely used as the impedance standards for an on-wafer measurements. A fabrication process providing the highest precision dimensions are basically required for ISS, and thus the printing technology should provide high-precision, durability, reproducibility and reliability in the ISS fabrication. This means that the demonstration of ISS fabrication and measurements represents the capability of fabrication technology. On the substrate in this paper, short circuits, open circuits and transmission lines with length,  $L$ , 220  $\mu\text{m}$ , 450  $\mu\text{m}$ , 900  $\mu\text{m}$ , 1800  $\mu\text{m}$ , 3500  $\mu\text{m}$ , and 5350  $\mu\text{m}$ , were prepared. Target thickness of conductor is 1.0  $\mu\text{m}$ .

### C. Dimensional Measurements

A Keyence laser interferometer and precision X-Y stage were used to measure the profiles of CPW transmission lines formed at different baking temperature. Following dimensions and structures were measured and evaluated for printed CPW transmission lines;

- signal line width
- gap spacing between signal and ground lines
- uniformity of line width and gap spacing along with length direction.
- thickness of conductor
- surface roughness of conductor
- edge contour of conductors

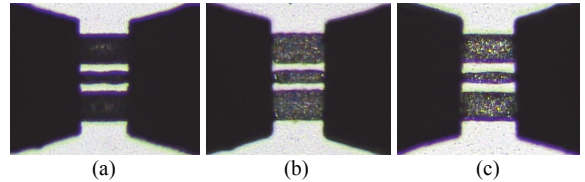


Fig 1 Transmission lines formed by screen printing technology, baking temperature of (a) 150 °C, (b) 600 °C and (c) 800 °C.

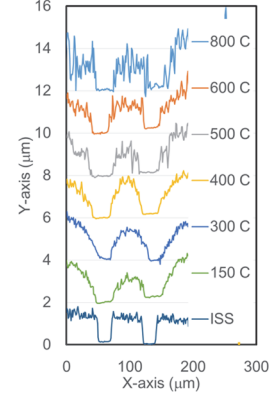


Fig 2 Cross sectional views of CPW lines formed by screen printing together with CPW lines on a commercial ISS.

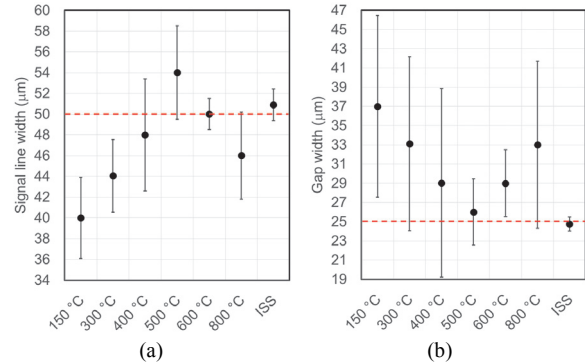


Fig 3 dimensional measurement results of (a) signal line width and (b) gap spacing. Error bars indicate their uniformities along with line length. Broken red lines indicate design values of line and spacing of CPW lines.

Figure 1 shows typical shape of CPW lines formed by screen printing technologies and subsequent baking process with various temperatures. For the samples, line patterns are not uniform along with line length. In addition, conductor line size was shrunk by baking at 800 °C, thus gap width was widely. Other important parameter is edge contours of the both signal and ground conductors (figure 2). Sharpness of edge contours is getting better by increasing baking temperature. Sharp edge at the signal line and ground lines are achieved in the CPW lines formed by baking at 500 °C and over. It seems to be likely as the shape of lines on ISS. However, the edge of conductors are rounded for the CPW lines formed at lower temperature, i.e. lower than 500 °C.

Figures 3 shows the measurement results of width of signal line and gap spacing. Error bars indicate uniformity of width and spacing along with line length. Signal width, as shown in figure 3(a), depends on baking temperature. Optimum dimension of signal line was realized by baking at 600 °C. Furthermore, very small distribution of the width values was realized in the CPW lines formed at 600 °C. The quality of signal line was comparable with the commercial ISS

Table I. Thickness of conductors

Temperature	Thickness ( $\mu\text{m}$ )		
	Ground-1	Signal	Ground-2
150 °C	2.22	1.17	2.70
300 °C	2.04	1.05	2.41
400 °C	1.77	0.9	2.07
500 °C	1.98	1.11	2.27
600 °C	2.01	1.32	1.56
800 °C	1.77	0.51	1.59

Table II. Surface Roughness

Temperature	Surface Roughness ( $\mu\text{m}$ )		
	Ground-1	Signal	Ground-2
150 °C	0.24	0.30	0.31
300 °C	0.26	0.36	0.3
400 °C	0.28	0.40	0.29
500 °C	0.57	0.61	0.43
600 °C	0.38	0.40	0.38
800 °C	0.49	0.28	0.35

fabricated by plating and photolithography techniques. Gap spacing, as shown in figure 3(b), also depends on baking temperature. Baking temperature of 500 °C provides an exact dimensions as same as design values. The temperatures of 400 °C and 600 °C produce gap close to a design value of gap spacing. Other important dimensional factor is uniformity of gap spacing along with line. The uniformity represented by error bars in the figure is small,  $\pm 4.0 \mu\text{m}$  in CPW formed at 500 °C and 600 °C baking temperatures.

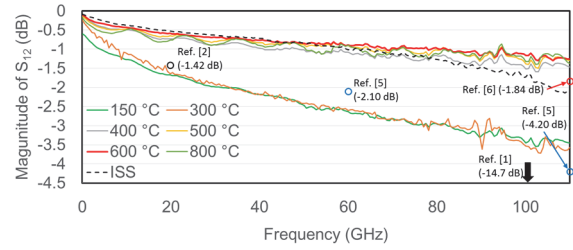
Table I summarizes the measured conductor thickness of conductors. Thickness of signal line are thinner than that of ground lines. Open area on the screen mask for signal line is smaller than printing area of ground lines due to line width difference. Furthermore, amount of ink depends on open area, and thus, thickness might be different for each pattern. However, signal and ground lines thicknesses are independent of baking temperature. They are almost 1.0  $\mu\text{m}$  for signal line and 2.0  $\mu\text{m}$  for ground lines, except in CPW lines formed at 800 °C.

Table II listed the evaluation results of surface roughness of conductors which is important for insertion loss of conductor at millimeter wave frequency. Low temperature baking of 150 °C achieves better surface roughness. However, higher temperature provides roughness of conductor by dissipation of binder materials from the conductor ink.

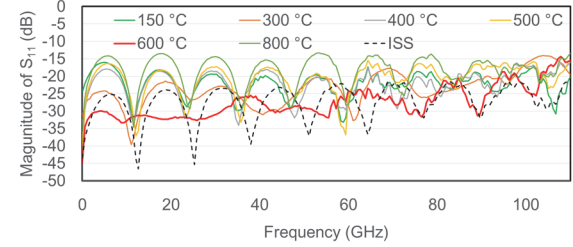
### III. Scattering Parameter Measurements and Results

#### A. Measurement System and Procedure

A Keysight Technologies (formerly Agilent Technologies) N5250A constructed by E8361A vector network analyzer and 1.0 mm frequency extension modules with mm-Wave controller were used to measure the S-parameter of CPW lines in the range from 10 MHz to 110 GHz. 1.0 mm coaxial probes, Cascade MicroTech Infinity SP-I110-A-GSG-06 with 150  $\mu\text{m}$  pitch, were used. Probes was somewhat over driven in order to making good contact to CPW, even if the thickness is difference of signal and ground conductors of CPW. It is not need to worry about breaking a probe due to soft conductor of CPW.



(a)



(b)

Fig 4 Scattering parameter measurement result of 5250  $\mu\text{m}$ -long transmission lines formed by screen printing technology. (a)  $S_{12}$ . (b)  $S_{11}$ .

First, TRL calibration was performed on Cascade Microtech 101-190C ISS at the probe tips. In the case of calibration at probe tip using ISS, “thru” line,  $L=220 \mu\text{m}$ , is used as “flush thru”, then, uncorrected factor of insertion loss of “thru” line remained in VNA measurement results after the on-wafer calibration. It thus provided “offset insertion loss” in the measurement. In the investigation of insertion loss per unit length, four sets of long CPW lines with five different lengths were measured for each printed sample. After making loss per unit length can be calculated from the slope of the graph. As the result, “offset insertion loss” can be ignored from the graph of length dependence of insertion loss, the insertion on the measurement results.

Furthermore, measurement of a short circuit was performed and repeated ten times ( $N=10$ ) in order to investigation of the contact reproducibility at a probe tip. Contact reproducibility performance depends on capability of hardness and adhesion of conductor metals of CPW lines.

#### B. Results of Scattering Parameter Measurements

S-parameter measurement results of CPW lines are shown in figures 4. There are averaged S-parameters for a 5250  $\mu\text{m}$ -long CPW line formed at each baking temperature. From figure 4 (a),  $S_{21}$ , insertion loss, is almost the same value of CPW line on commercial ISS, 1.0 dB at 60 GHz and 1.5 dB at 110 GHz, except for lines formed at 150 °C and 300 °C. CPW lines formed at 150 °C and 300 °C have approximately 2.5 times loss of others. In addition, line formed at 600 °C achieved no ripple on  $S_{12}$  trace due to small  $S_{11}$ , reflection characteristics, as shown in figure 4(b).  $S_{11}$ , reflection characteristics, of CPW lines formed at 600 °C is the best value in this paper. Reflection characteristics in the line are most sensitive to signal width compared to gap width. Thus almost 50  $\Omega$  characteristic impedance in CPW lines formed at 600 °C is achieved by almost the same signal width of a commercial CPW line. Furthermore, resulted  $S_{21}$  characteristics also have a significant advantage over previous research achievements [1, 2, 5, 6]. Other printed CPW lines

generate large reflection characteristics over the entire frequency range. This means that characteristic impedance of printed CPW lines are out of match with characteristic impedance 50 Ω of a probe tip.

Relationship between  $S_{11}$  and  $S_{12}$  as shown in figure 5 can make an accurate understanding of an optimum fabrication conditions for CPW lines formed by screen printing technology. The best CPW line have usually low reflection characteristics and low insertion loss. In this case, a characteristic of the best lines are plotted at the top-right in figure 5. Broken lines indicate 2-dimensional 2 σ distributions as follows;

$$2\sigma(M) = 2\sqrt{\sigma^2(S_{11})S_{11}^2 + \sigma^2(S_{12})S_{12}^2 + 2r(S_{11}, S_{12})\sigma(S_{11})\sigma(S_{12})S_{11}S_{12}} \quad (1).$$

Here,  $\sigma(S_{11})$  and  $\sigma(S_{12})$  are the standard deviations in  $S_{11}$  and  $S_{12}$ ,  $r(S_{11}, S_{12})$  is the correlation coefficient between  $S_{11}$  and  $S_{12}$ . As the result, baking at 600 °C is the best condition to provide low value and low distribution of insertion loss, and in agreement with dimensional measurement results.

From the results of insertion loss per unit length (dB/mm) as shown in figure 6, CPW lines baked over 500 °C achieved the same value of CPW on commercial ISS at 60 GHz and smaller value at 110 GHz. This means crystallization of silver paste were accelerated over 500 °C.

### C. Contact Reliability of Conductor Metal

Figures 7 show experimental standard deviation (N=10),  $1\sigma$ , of magnitude and phase of  $S_{11}$  values for short circuit measurements. Ten discontact and recontact cycles were made at the same probe position. Figure 7(a) shows contact reproducibility of  $S_{11}$  magnitude of short circuit. Some of difference can be shown, but difference, less than 0.003 dB, is comparable to system drift. For phase measurement reproducibility, CPW lines on ISS provides at least 0.10 degrees large deviation compared to printing CPW lines. Mechanical properties of printing conductors is equivalent to conductor formed by plated technology.

## IV. Conclusions

This paper presented capability of screen printing as an innovated fabrication technology to use for millimeter-wave applications and precision measurement systems. CPW lines formed at 600 °C baking achieved low insertion loss and low reflection characteristics up to 110 GHz and comparable to the CPW lines on the commercial ISS. Screen printing technology leads simultaneously to precision forming, mass production and therefore cost efficiency and environmental acceptability.

### Acknowledgment

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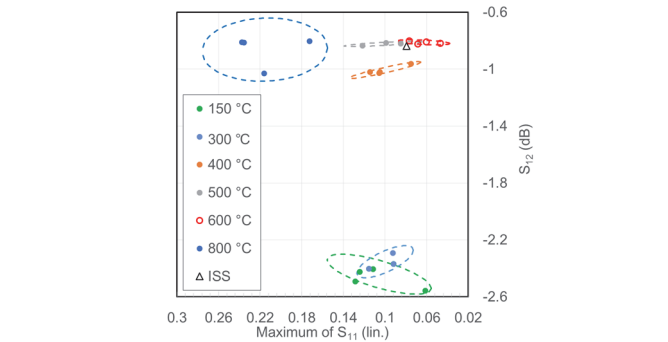


Fig 5 Relationship between values of  $S_{12}$  and peak values of  $S_{11}$  around 60 GHz (60 GHz ± 5 GHz) for CPW lines formed by different baking temperature together with ISS.

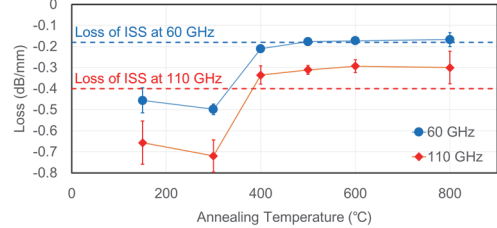


Fig 6 Insertion loss per unit length (dB/mm) of CPW lines formed by screen printing technology. The both broken lines indicate insertion loss per unit length of CPW lines on ISS.

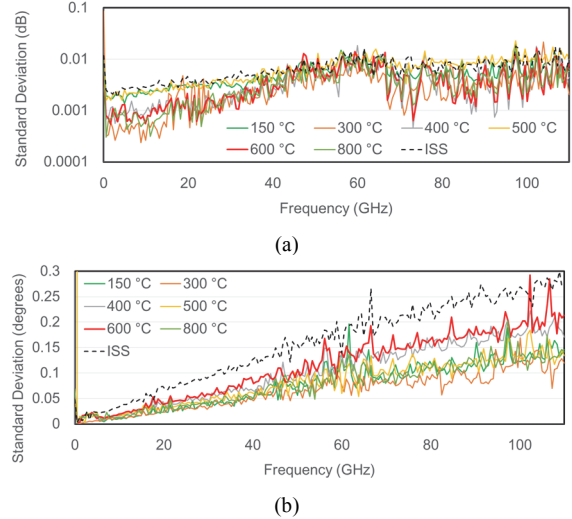


Fig 7 Reproducibility performance for conductor formed by screen printing technology, (a)  $S_{11}$  magnitude, (b)  $S_{11}$  phase of short circuits.

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