Silver screen printed transmission lines - influence of substrate porosity on the RF performance and modelling up to 30GHz

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Silver Screen Printed Transmission Lines- Analyzing the Influence of Substrate Roughness on the RF Performance up to 30 GHz

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Abstract
In this paper, the authors investigate the influence of DC conductivity on the RF performance of screen printed traces on a flexible substrate. From literature, much work has been done on the effect of sintering conditions on the electrical resistivity of printed traces. Typically the traces were printed onto substrates with negligible surface roughness. Yet this would not be the case for printing on textiles for wearable electronics applications. In this paper, we investigate the electrical resistivity of screen printed traces on a substrate which is similar to fabrics, in that it is flexible and has non-negligible surface roughness (Ra≈1μm). In particular, an accurate simulation model was developed to correlate with the measurement results, which would provide guidelines for the modelling of similar printed traces to predict their RF performances.

Introduction
Wearable electronics are becoming increasingly popular for a myriad of applications spanning from medical (monitoring health and physiological conditions of its wearer) to consumer products. Realizing conductive traces on flexible substrates is crucial for wearable electronics, and techniques such as the use of conductive threads, screen printing and inkjet printing have been considered in literature [1].

Much literature abounds on the effect of sintering conditions on the electrical resistivity of printed traces [2-7]. However, those traces were typically printed onto substrates with negligible surface roughness. For instance, Kim et al [6] characterized the RF performance of inkjet-printed transmission line up to 30 GHz on silicon wafers. They related the reduction in the resistivity (with increasing sintering temperature) to the improvement in the measured insertion loss. Salmeron et al [7] characterized the resistivity of both screen printed and inkjet printed test structures on smooth substrates such as Kapton, Polyethylene Terephthalate (PET) and Polyethylene naphthalate (PEN). The resistivity values were then input into simulation models in the design of coil antennas operating at a frequency of 13.56 MHz.

In this paper, the authors seek to investigate the influence of DC conductivity on the RF performance (≤30 GHz) of screen printed traces on a flexible substrate (Rogers RO3006™) with non-negligible surface roughness (Ra≈1μm). The final goal would be to correlate the RF measurements with an accurate simulation model, with the aim of using the simulation model to predict the RF performances of future printed traces. Such models would also be applicable for transmission lines realized by inkjet printing [6-7] or other printing techniques [8].

Methodology
The methodology for this work is as shown in Fig. 1:

Fig. 1. Methodology used in this work.

Firstly, 50Ω coplanar waveguide (CPW) transmission lines were designed for the RO3006™ substrates. As the degree of the silver paste spread onto RO3006™ is unknown, these designs include signal-ground gaps with varying dimensions to compensate for the paste spread. The paste spread varies for different paste-substrate combination and needs to be characterized separately. After the designs are completed, the screen mask would be fabricated for the screen printing. Prior to printing on RO3006™, screen printing trials were first conducted onto PET substrates to ensure that the designs were not short-circuited by the paste bleed. Subsequently the designs were screen printed onto the RO3006™ substrates and
Simulation would also provide insights into previous work, the silver content of 65-70% with a viscosity of 300 cP. Resistivity could be measured for each CPW structure (Fig. 3). These structures were positioned beside the CPW transmission lines such that an in-situ measurement of the DC resistivity could be made for each CPW structure (Fig. 3).

The test structures were fabricated in a 320 x 320 mm screen, using a mesh count of 640, an emulsion thickness of 7 μm and an open area of 39%. The silver paste used has a silver content of 65-70% with a viscosity of 85 Pa.s at 25°C.

Sample Preparation

RO3006™ [10] is the high frequency PTFE composite substrate used for the screen printing (relative dielectric constant: 6.5, loss tangent: 0.002 at 10 GHz). The substrate thickness is 1.27 mm, and one side of the copper layer was chemically etched off to expose the substrate underneath for the screen printing. The borosilicate glass had a thickness of 1.1 mm, with a relative dielectric constant of 4.8 and loss tangent of 0.004 at 1 MHz.

The test structures in the screen mask include (a) 4 point probe structures and (b) 50Ω CPW structures spanning 2 mm to 21 mm lengths. The signal width and signal-ground spacing of the CPW on RO3006™ are designed as 150/75 μm. Based on previous work, the paste spread for the particular silver paste used was around 25 μm, which translates to printed dimensions of around 175/50 μm. The 4 point probe test structures had widths corresponding to the signal and ground traces. These structures were positioned beside the CPW transmission lines such that an in-situ measurement of the DC resistivity could be made for each CPW structure (Fig. 3).

The test structures were fabricated in a 320 x 320 mm screen, using a mesh count of 640, an emulsion thickness of 7 μm and an open area of 39%. The silver paste used has a silver content of 65-70% with a viscosity of 85 Pa.s at 25°C.

Simulation Model

The 3D model used for the correlation is simulated using a time domain (TD) solver in CST, as shown in Fig. 5. A waveguide port was used to excite the structure. Due to the small thickness of the silver traces (~8.5 μm) and the non-negligible skin depth of 2.9 μm at 30 GHz, a need exists to mesh adequately within the trace thickness in order to capture the skin effect on the transmission line loss. Apart from adequately meshing the trace thickness, it was also important to mesh for the trace edges of the trapezoidal trace so as to capture the current crowding effect in those areas.

The trace profile dimensions used in the 3D model were averaged from several measured sections spanning the entire transmission line length. This was done using a post-processing function in the OLS4100 software.
The 3D model was validated by comparing the S-parameter results with those obtained from a frequency domain (FD) solver available in the same software. As shown in Fig. 6, the S-parameter results between the 2 solvers were compared for a 7 mm CPW structure on RO3006™. In Fig. 6, a good agreement between the two models is obtained. The variation observed between the two set of results could be attributed to numerical error and material characterization, since the material characterization is treated differently between the FD and TD models.

Results and Discussion

Fig. 7 shows the regions containing test structures for DC measurements. The different regions were considered in order to evaluate the variation of the DC conductivity values extracted from the 4 point probe measurements. The measured DC conductivity values on RO3006™ were compared with borosilicate glass as shown in Fig. 8. DC structures with widths of 150 µm and 690 µm were used for the comparison. The trace thicknesses range from 6.3-7.9 µm on borosilicate glass and 7.2-9.5 µm on RO3006™.

A few observations can be made from the results shown in Fig. 8. For wider traces (690 µm) a larger variation of the extracted DC conductivity is observed on RO3006™ compared to borosilicate glass. Using the average DC conductivity value as the reference value, the variation in DC conductivity (for narrower traces 150 µm) fall in the range of 10-16% for both substrates. In addition, the DC conductivity range on RO3006™ is consistently higher compared to those on borosilicate glass. The extracted range on RO3006™ is from 7.7 x 10^5 S/m-1.1x10^6 S/m, compared to a lower range of 4.5x10^5-7.6x10^5 S/m on borosilicate glass. The higher range of DC conductivity obtained for RO3006™ may be attributed to the longer effective widths of the printed traces on a substrate with non-negligible surface roughness [11], which is
not being accounted for in the extraction of the DC resistivity. Fig. 9 and Fig. 10 show the variation in the substrate surface between RO3006™ and borosilicate.

Overall, the DC resistivity range obtained for traces on RO3006™ (10x10⁻⁵ - 12x10⁻⁵ Ω-cm) is close to the value provided by the paste manufacturer, which suggests that they may have reached saturation point due to the paste fillers present in the formulation. This limitation implies that a lower DC resistivity value may only be possible through the use of a different paste formulation.

![Fig. 9. Cross-section of silver paste on borosilicate glass.](image)

![Fig. 10. Cross-section of silver paste on RO3006™ substrate.](image)

The measured DC conductivity values were then input into the 3D model of a 2 mm transmission line. The corresponding measured trace parameters which were used in the 3D model are provided in Table 1. The measured RF performance of the transmission line is shown in Figs. 11 and 12.

<table>
<thead>
<tr>
<th>Trace parameters with reference to Fig. 2</th>
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<tbody>
<tr>
<td>w(μm)</td>
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<td>-------</td>
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<td>160</td>
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![Fig. 11 Correlation of simulation and measurement results (S₂₁).](image)

![Fig. 12 Correlation of simulation and measurement results (S₁₁).](image)

From Fig. 11, a good correlation is obtained between simulation and measurement up to 30 GHz. Varying the DC conductivity value (i.e. corresponding to the lower conductivity range) in the 3D model was not found to affect the transmission loss significantly (variation ≤ 0.1 dB).

In particular, the effect of the trace edges was investigated for the 2 mm transmission line in the correlation. When sharp trapezoidal edges were used to model the printed traces in the simulation model, the losses (S₂₁) were found to be overestimated by about 14% as shown in Fig. 11, with the effect on the return loss being negligible (Fig. 12). In modeling the trapezoidal corners as curved edges, a good match could be obtained between the simulation and measured results. This effect would be further investigated in future work involving the correlation of longer transmission line lengths.

**Conclusions**

The important results in this work are as follows:

- The substrate roughness was observed to influence the DC conductivity of screen printed traces. The DC conductivity values extracted from a PTFE-based substrate are at least 1.4 times larger compared to borosilicate glass substrates. This may be attributed to the longer effective widths of the
printed traces on a substrate with non-negligible surface roughness [11], which is not being accounted for in the extraction of the DC resistivity.

• A correlation of the simulation and measurement results was performed for a 2 mm CPW line, with a good match obtained up to 30 GHz. The results obtained are encouraging towards the goal of obtaining an accurate 3D model to estimate the RF performance of printed traces.

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