Conductivity Measurements of Silverpastes

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Abstract

The development of three-dimensional printed circuit boards requires research on new materials which can easily be deformed. Conducting pastes are well suited for deformation even after they are applied to the dielectric carrier. This paper deals with measurements of the electrical conductivity of these conducting pastes. Two different conductivity measurement techniques are explained and carried out. The resulting measurements give an overview of the conductivity of several measured samples.

Keywords: conductivity, conducting pastes, 3d circuits.

1 Introduction

Current printed circuit board (PCB) production is still mostly based on the well-known concept of laminating and photo-etching. During the laminating process, the whole surface of the dielectric carrier is covered with a conducting material such as copper. Then the conducting material is covered with a photosensitive polymer and exposed to a light projection of the desired circuit. After washing, only the desired circuit surfaces are covered with the polymer. Using a highly corrosive etching fluid, the conducting material not covered by the polymer is removed, leaving only the circuit.

The disadvantages of this method are on the one hand the use of conducting material that will be discarded. This is costly. On the other hand, the laminating process uses high pressure to bond the conductor with the dielectric carrier. This bonding can therefore only be applied to hard flat surfaces, such as standard dielectric carriers. These flat surface PCBs are ill-suited for deformation, which limits their application in the growing market for 3D shaped circuit boards.

One way to solve this problem is to use Molded Interconnect Device materials in combination with Laser Direct Structuring (LDS) [1]. In MID-LDS, the dielectric carrier is preformed into the desired shape. Then the surface of the dielectric carrier is covered with an organic metal complex. The organic metal complex can be activated using a laser beam. The activated surface is roughened, and the organic metal complex is separated into metal atoms and organic ligands. This makes the activated surface suited for copper coating with a strong grip. After cleaning, the copper coating is then built up on the activated areas using a current-free copper bath.

Another approach is to use thin flexible dielectric carriers together with a moldable conductor, such as conducting pastes. In this approach, the conductor is first applied to the surface of the dielectric carrier using a printing technique like that used for ink printers. The shape of the applied circuit has to take into account the desired form of the circuit after deforming. The dielectric carrier together with the conductor are then deformed into the desired shape. The advantages clearly lie in the straightforward processing steps.

Most conducting pastes consist of conducting material dissolved in an epoxy, polyamide or acrylate adhesive. After applying the paste, the material is heated in order to thoroughly bond the conductor to the carrier and remove the solvent from the conducting structure. The resulting conducting structure is studied for its conductivity and usability for high frequent PCB designs. This paper presents two methods for measuring the electrical conductivity of such conducting pastes.

2 Microstrip T-resonator measurement structure

The microstrip T-resonator is a two-port resonator which consists of a 50Ω microstrip line with a parallel quarter wavelength resonating line [2]. Figure 1 shows the layout of the T-resonator used here. The open-ended quarter wavelength transmission line stub, resonates at odd integer multiples of the quarter wavelength frequency. The first resonance can be determined by calculating the length of the quarter wavelength stub, as follows

$$L_{el} = \frac{nc}{4f\sqrt{\epsilon_{reff}}} \quad (1)$$

where n is the order of the resonance (here $n = 1$), c is the speed of light, f is frequency, ϵ_{reff} is the effective dielectric constant for the dielectric carrier that is used. The line length of the quarter wavelength stub is calculated to have the primary resonance at 500 MHz. In order to get the first resonance as accurately as possibly at 500 MHz, corrections must be applied for open-end and T-junction effects. These effects where compensated with the use of Agilent ADS commercial software. The accurate designing makes it possible to have data points at the desired frequencies.

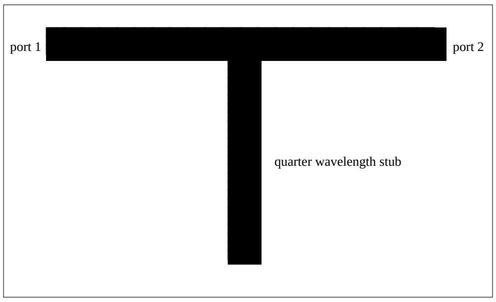

Fig. 1: Basic layout of the T-Resonator measurement structure

The T-resonator operates like a notch filter with a resonant null in the resonance frequencies. A network analyser (NWA) is used to measure the transmission of the two-port network. From the measurement it is possible to determine the loaded quality factor Q_L by finding the resonance frequencies and the corresponding 3 dB bandwidths BW_{3dB}. The loaded quality factor is the calculated as

$$Q_L = \frac{f}{BW_{3dB}} \tag{2}$$

The loaded quality factor is influenced by the 50 Ω test set of the NWA. In order to compensate, the unloaded quality factor Q_0 has to be extracted

$$Q_0 = \frac{Q_L}{\sqrt{1 - 2 \cdot 10^{-(L_A/10)}}} \tag{3}$$

where L_A is the insertion loss in dB at the resonance. The unloaded quality factor Q_0 comprises the three main loss effects, namely conductor, dielectric and radiation losses [3].

$$Q_0^{-1} = Q_c^{-1} + Q_d^{-1} + Q_r^{-1} \tag{4}$$

where Q_c is the quality factor due to conductor losses, that we want to derive, Q_d is the quality factor due to dielectric losses, and Q_r is the quality factor due to radiation losses. The T-resonator is first implemented using a known conductor, copper, and a reference measurement is carried out. For copper, the attenuation due to conductor loss can be obtained with [4]

$$\alpha_c = \frac{R_s}{Z_0 W} \tag{5}$$

where $R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$ is the surface resistivity of the conductor. Using (5), the quality factor due to conductor losses can be calculated as

$$Q_c(copper) = \frac{\beta}{2\alpha} \tag{6}$$

Now it is possible to derive the sum quality factor of both other losses from the measurement with

$$Q_{ref}^{-1}(copper) = Q_0^{-1} - Q_c^{-1} \tag{7}$$

It is assumed here that the losses due to the dielectric carrier and radiation are equal for the reference measurement with the copper conductor and for the measurements carried out using the conducting pastes, if the same dielectric carrier is used and the dimensions of the resonator are equal. The surface resistivity R_s and further the electrical conductivity σ can be derived by calculating equations (7), (6) and (5) backwards for the measured sample.

There is limited accuracy, due to the relatively small quality factor and the assumption that the dielectric and radiation losses are equal for the copper and for the samples. Only assumptions can be made about the global location of the electrical conductivity.

3 Surface resistance measurements by means of a dielectric resonator

The methods described in this section are based on the findings of J. Krupa [5]. The measurements are performed using a dielectric resonator, manufactured by QWED. In a completely closed resonator, the unloaded quality factor comprises only the quality factor due to conductor losses Q_c and the quality factor due to dielectric losses Q_d. The unloaded quality of a resonator which is completely filled with a dielectric material can then be described as

$$Q_0^{-1} = \frac{R_{ss}}{A_{sup}} + \frac{R_{sm}}{A_{met}} + p_e \tan\delta \tag{8}$$

where A_{sup} and A_{met} are geometrical factors for the conducting surfaces of the resonator, the former for the surface of the sample and the latter for the lateral metal parts of the resonator. R_{ss} and R_{sm} are the corresponding surface resistance values for sample and metal. p_e is the fraction of the electrical energy stored in the dielectric material, and $\tan\delta$ is its dielectric loss tangent value.

Although equation (8) is valid for any of the resonator modes, only the $TE_{0\rho\phi}$ modes are considered for the conductivity measurements. The $TE_{0\rho\phi}$ modes are chosen because they have both axial symmetry and ohmic contact between the surface of the sample, and the lateral metal conductor has no influence on the quality factor of the resonance. This lack of influence results in high reproducibility for experiments using the same pair of samples. For the measurements, the TE_{010}, TE_{011} and TE_{012} modes are used to determine the electrical conductivity of the sample.

In order to eleminate the surface resistance of the lateral metal conductor in (8), first a measurement is made using samples of the same material as the metal.

Using the measured unloaded quality factor as a reference Q_{0ref} it is possible to write (8) as

$$R_{ss} = A_{sup}Q_0^{-}1 - \frac{A_{sup}^2}{A_{sup}+A_{met}}Q_{0ref}^{-1} - \frac{p_e \tan\delta}{A_{sup}^{-1}+A_{met}^{-1}} \quad (9)$$

With equation (9) it is now possible to determine the surface resistance of the sample, and from this to derive the electrical conductivity. The accuracy of the measurement depends on measuring the unloaded quality factor, the uncertainty of the dielectric loss tangent value and the values of the geometrical factors. The former is resolved by adjusting both the coupling loops to have a maximal transmission S_{21} of $-40dB$, which results in a maximum error for Q_0 of 1%. Both the other values are provided by the manufacturer. The accuracy of the measurement using the dielectric resonator relies on the assumption that the conductor deposit is bulk. The deposited conductor is only assumed to be bulk if its thickness is at least 3δ, where $\delta = \frac{1}{\sqrt{\pi f \kappa \mu}}$ [6]. If the deposited conductor is thinner, the electromagnetic field can in part penetrate through the conductor into the carrier. The dielectric losses of the carrier will then have an effect on the quality factor of the measurment. For samples with a minimum of 3δ, the maximum accuracy, taking into account the error of Q_0, is 2 % for the surface resistance and 5 % for electrical conductivity.

4 Measurements

The T-resonator structure is implemented using a Rogers RTDuroid 5880 laminate. Figure 2 shows the resulting resonator structure, a copper structure on the left and a structure with a sample conducting paste on the right. The reference sample in copper was created using a photo-etching technique. In order to check for connectivity errors, the T-resonator sample structures were created once using a copper conductor with a quarter wavelength stub printed on top using the conducting paste, and in the other case both transmission line and quarter wavelength stub were printed using the conducting paste. For these measurements it has to be taken into account that the laminate was possibly unsuited for the preparation and for the heating steps required for applying the conducting pastes, resulting in higher inaccuracy of the measurements. Figure 3 presents the resulting transmission measurements. Two resonant points can be seen, one at approximately 500 MHz and one at 1.5 GHz. Several samples with different pastes were then measured, and the results can be found in Table 1.

Fig. 2: The T-Resonator Structure

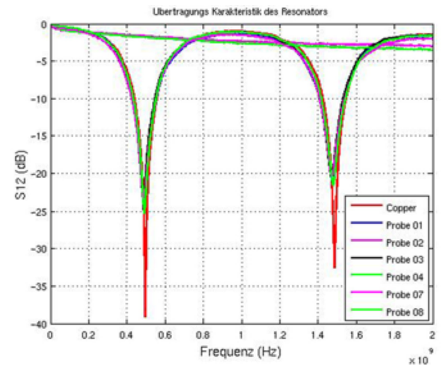

Fig. 3: Transmission measurement of the T-Resonator Structure

Table 1: Electrical conductivity measurements using the T-resonator structure

Sample	σ [S/m] @500 MHz	σ [S/m] @1.5 GHz
01	3E6	3E6
03	2E6	3E6
07	2E6	3E6
08	3E6	4E6

The dielectric resonator uses samples with surface dimensions of approximately 9.5 cm times 9.5 cm on both the top side and the bottom side of the resonator. Using the dielectric resonator, the copper samples are first measured as a reference. The copper samples are laminated surfaces of Rogers RTDuroid 35 μm in thickness. The actual samples are squares of conducting pastes printed on a dielectric carrier with an approximated thickness of 10 μm, which was the current depositing limit. This is less than the formerly defined 3δ that is needed for the assumption of a bulk conductor. However, considering the high reproducibility of the measurements, and taking into account that all samples use the same carrier and have the same depositet thickness, it is still possible to make a qualitative evaluation of the differences between the measured samples. The resulting conductivity measurements are shown in table 2.

Table 2: Electrical conductivity measurements using the dielectric resonator

Sample	σ [S/m] @1.6 GHz	σ @2.1 GHz	σ @2.7 GHz
Copper	5.53E7	5.35E7	5.65E7
07120902	5.89E+006	5.61E+006	5.43E+006
07120910	5.35E+006	4.98E+006	5.50E+006
07120913	4.42E+006	4.35E+006	4.48E+006
07120914	4.45E+006	4.47E+006	4.73E+006
07120915	4.40E+006	4.63E+006	4.62E+006
07120916	4.35E+006	4.68E+006	4.63E+006
07120917	5.50E+006	5.72E+006	5.67E+006
07120918	5.50E+006	5.50E+006	5.50E+006

5 Conclusion

A T-resonator structure for measuring electrical conductivity has been realised for 500 MHz and 1.5 GHz. Further, a dielectric resonator has been evaluated and acquired for accurate measurements at 1.6 GHz, 2.0 GHz and 2.7 GHz. Taking into account the accuracy of the measurements it is possible to make a qualitative evaluation of the different conducting pastes.

The electrical conductivities of the sample conducting pastes were measured using the T-resonator and the dielectric resonator. The conductivity of the conducting pastes has been shown to be approximately 10 % of the electrical conductivity of copper. Although the conductor losses for the conducting pastes will be larger than in the case of copper, they are still usable for designing high frequent circuits.

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