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Quality Control Testing of Interdigitated Circuits with Impedance Spectroscopy

Roshaun Titus
School of Materials Science and Engineering
College of Engineering,
Georgia Institute of Technology
Atlanta, Georgia. United States
rtitus6@gatech.edu

Rosario A. Gerhardt
School of Materials Science and Engineering
College of Engineering,
Georgia Institute of Technology
Atlanta, Georgia, United States
rosario.gerhardt@mse.gatech.edu

J. Elliott Fowler
Materials Characterization and Performance
Sandia National Laboratories
Alburquerque, New Mexico, United States
jfowle@sandia.gov

***Abstract*—Electronic components are affected by several environmental factors, including relative humidity during operation. When fabricating multiple identical components, it is important to ensure all variables involved in the fabrication of each component are equal. Impedance spectroscopy holds potential for verifying whether components are identical to one another, as it can test a material's response using AC voltage throughout a range of frequencies. In this paper, impedance spectroscopy is used to determine the response of two identically made circuit boards with 5 interdigitated circuits each. Statistical methods are performed to determine the repeatability of the measurements at each circuit location, then the average for all 5 circuits on a single board as well as the comparison between boards. It was found that repeatability at each location shows small errors but that significant differences existed between the 5 identically fabricated circuits on a single board and between boards. Statistical methods were used to test for both the measurement accuracy and production accuracy.**

Keywords—impedance, frequency, error, repeatability, reproducibility.

I. INTRODUCTION

Impedance spectroscopy was used to characterize several solder masked circuit boards with interdigitated circuits as shown in Fig. 1(a). Fig. 1(b) and 1(c) display the appearance of a positive and a negative electrode tip. Each circuit is comprised of 25 comb leads from a positive electrode and 25 comb leads from a negative electrode aligned in succession, parallel to one another. Five circuits are arranged on the boards, each with an equivalent arrangement where respective leads for measurement are connected at the lower ends of the boards, as shown in Fig. 1(a). These circuit boards were mainly categorized into coated and uncoated boards. In this study two uncoated boards were analyzed: Sample7 and Sample8. Using impedance spectroscopy, it is possible to quantify the characteristic differences between the circuits on a single board and between multiple boards as a function of frequency and location. Measurements were done under relative humidity levels of ~50%RH and temperature ~21°C. Investigated are the similarities and differences of the uncoated boards using statistical relations between individual circuits of each board.

II. METHODS

A. Impedance Spectroscopy

Impedance measurements were performed using a Solartron SI 1260 and Solartron 1296 Dielectric Interface, operated using SMaRT Impedance Measurement software. Measurements were taken for all five circuits on each board. Three runs/tests were performed per circuit to verify the impedance response being measured. Each run measured the impedance magnitude (|Z|), phase angle (Θ), real (Z'), and imaginary (Z").[1] Measurements were performed at an AC voltage of 500 mV through a frequency range of 100 mHz to 10 MHz at 15 steps per decade with zero DC voltage applied, resulting in 121 data points per property and run. Samples were placed in an ETS Humidity Chamber to have a controlled relative humidity (RH) environment, controlled using an ETS Dehumidifier Controller. Alligator clips were used for connecting circuit leads to the 1296 Dielectric Interface.

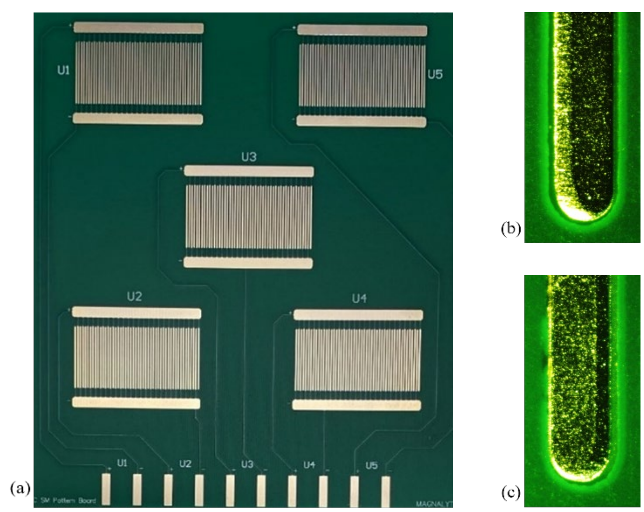

Fig. 1. (a) Image of sample circuit board. (b) and (c) are optical images of one positive and one negative electrode.

B. StatisticalMethods

Numerical representations of the quality of the boards were computed using MATLAB. Differences between runs were calculated for each of the measured properties. Calculations are

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made per frequency for each property. Between the three runs of a circuit, the average, standard deviation, and percent error is calculated per frequency for each of the four properties using the following set of equations.

$$\bar{x}(k) = \{\Sigma\, x(i)\} \,/\, n \tag{1}$$

$$d(k) = \mathrm{sqrt}(\Sigma\{|x(i) — \bar{x}|^2\} \,/\, (n — 1)) \tag{2}$$

$$std(k) = (d \,/\, |\bar{x}|) * 100 \tag{3}$$

$$abs(k) = \{|x(i) — \bar{x}| \,/\, |\bar{x}|\} * 100 \tag{4}$$

where: $\bar{x}(k)$ is the average per frequency k; x(i) is measured value per run or circuit i; n is the total number of runs or circuits measured; *d(k)* is the standard deviation per frequency; *std(k)* is the standard deviation percent error per frequency; and *abs(k)* is the absolute percent error per frequency. Average and standard deviations are calculated for each property, for each circuit (complex Z*, real Z' vs log f, imaginary Z" vs log f, |Z*| vs log f and θ vs log f). Three methods were used to calculate the percent error and were classified into two categories: repeatability of measurements at each location (3 runs for 121 frequencies each) and reproducibility from location to location. Repeatability refers to measurement repeatability at each location of the fabricated boards, quantifying equipment accuracy throughout all three runs performed on a circuit. Reproducibility refers to material reproducibility, quantifying the similarities or differences between the five circuits on a board. With percent error method one (PEM1), repeatability is obtained using equation (3) while percent error method two (PEM2) utilizes equation (4) per run of a circuit, then takes the average using equation (1). Percent error method three (PEM3) calculates reproducibility using equation (4), taking the difference of the board and circuit average rather than the average of each of the circuits. In each case, the errors for the 121 frequency data points are averaged. This results in the total percent error, summarizing the repeatability or reproducibility per property and circuit. When considering the three runs performed on each circuit, a single total percent error value is computed using 363 data points.[2]

III. Results

Multi-circuit Nyquist plots (Z" vs. Z') shown in Fig. 2, highlight the differences between all five circuits of Sample 8. They are plotted using the calculated average and standard deviation from the three different runs of each circuit. They all exhibit capacitive behavior that shows impedance decreases as the frequency is increased. Nyquist plots of the board averages for Samples 8 and 7 are shown in the inset of Fig. 2. Table I summarizes the errors calculated for the three different methods described (PEM1, PEM2 and PEM3) from the data collected from Sample 8. A similar table is obtained for Sample 7 but is not included due to space limitations. The Mean column is produced from taking the average across the total percent error values for each property per circuit, giving the overall circuit performance per method. The Board row is obtained by taking the average along the total percent error values per property, giving the overall board performance of that property per method. The intersection of Mean and Board represents an average either down the column or across the row, resulting in the overall board repeatability (PEM1, PEM2) or reproducibility (PEM3). Finally, a weighting factor is introduced to remove anomalous data before the total percent errors are calculated and this is shown in Table II. There are 121 percent error values per property of a circuit. For a given property and circuit, two frequency points with the greatest percent error are removed from the range of data, leaving only 119 points. This is done for each property and circuit, then the total percent errors are calculated similarly to what was done for Table I.

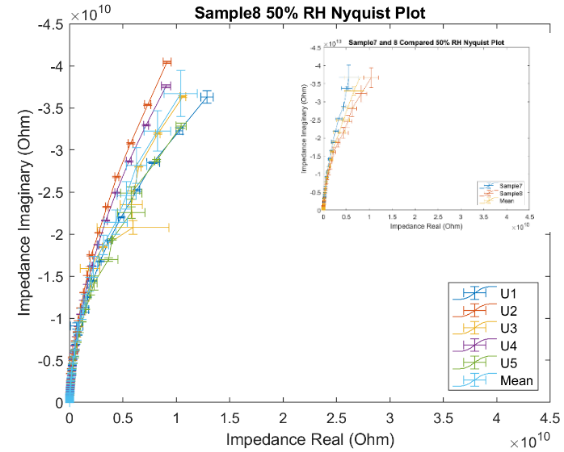

Fig. 2. Nyquist plots for all five circuits of Sample 8 as well as the board average (Mean) are plotted, including their standard deviations. The inset diplays a Nyquist plot that compares the board averages of Sample 7 and Sample 8. The average of both boards (Mean) with standard deviation is also included.

A. Repeatability

It was found that the real impedance (Z') for each circuit showed the greatest error. This is likely due to the incomplete semicircles obtained in the Nyquist plots due to the high impedance of the solder mask. This is a trend that is shared by each circuit of the uncoated boards. The Mean column represents the final error of each circuit and the board. Hence,

Table I. Sample 8 Total Percent error for PEM1, PEM2 and PEM3.

SD%	Sample8: PEM1 Repeatability per circuit					Sample8: PEM2 Repeatability per run					Sample8: PEM3 Reproducibility per board				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*	*|Z|*	*Θ*	*Z'*	*Z"*	*Mean*	*|Z|*	*Θ*	*Z'*	*Z"*	*Mean*
U1	0.170	0.173	3.477	0.182	1.000	0.128	0.128	2.623	0.136	0.754	2.413	0.279	4.738	2.374	2.451
U2	0.107	0.110	2.629	0.120	0.742	0.081	0.082	1.963	0.090	0.554	5.476	0.422	6.657	5.571	4.532
U3	0.124	0.213	2.029	0.160	0.631	0.094	0.161	1.521	0.121	0.474	1.517	0.167	3.826	1.543	1.763
U4	0.049	0.055	1.042	0.058	0.301	0.036	0.040	0.763	0.043	0.221	0.515	0.217	3.702	0.547	1.245
U5	0.216	0.130	1.522	0.193	0.515	0.165	0.098	1.142	0.146	0.388	6.840	0.370	6.084	6.903	5.049
Board	0.133	0.136	2.140	0.143	**0.638**	0.101	0.102	1.603	0.107	**0.478**	3.352	0.291	5.001	3.388	**3.008**

TABLE II. WEIGHTED TOTAL PERCENT ERROR PEM1 AND PEM3

SD%	Sample7: PEM1 (Weighted)					Sample8: PEM1 (Weighted)					Sample8: PEM3 (Weighted)				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*	*|Z|*	*Θ*	*Z'*	*Z"*	*Mean*	*|Z|*	*Θ*	*Z'*	*Z"*	*Mean*
U1	0.079	0.056	1.283	0.088	0.377	0.109	0.126	2.241	0.128	0.651	2.375	0.207	4.214	2.342	2.285
U2	0.055	0.025	0.760	0.058	0.224	0.085	0.084	2.019	0.098	0.572	5.425	0.361	6.285	5.498	4.392
U3	0.058	0.033	0.974	0.060	0.281	0.064	0.076	1.191	0.071	0.351	1.494	0.105	3.262	1.507	1.592
U4	0.057	0.034	1.020	0.059	0.293	0.039	0.044	0.946	0.048	0.269	0.501	0.166	3.385	0.518	1.142
U5	0.070	0.040	1.392	0.077	0.395	0.134	0.074	1.154	0.121	0.371	6.760	0.330	5.774	6.821	4.921
Board	0.064	0.038	1.086	0.068	**0.314**	0.086	0.081	1.510	0.093	**0.443**	3.311	0.234	4.584	3.337	**2.866**

they can be used for comparisons between circuits and samples. For each sample measured, the circuit with the highest and the lowest error differed. In spite of this, the trends for both PEM1 and PEM2 can be seen to have good agreement with one another. While U4 was found to have the most error in Sample 7 (not shown), U4 had the least error in Sample 8. This helps to confirm that the repeatability of a circuit is not a function of its location on the board. Besides the larger errors for the real impedance (<3,5%) found for location U1 in Sample 8, the total percent error values for all the other quantities are all below 0.6%, exhibiting great repeatability. Sample 7 gave greater repeatability over all circuits and properties (not shown).

B. Reproducibility

Referring to the inset in Fig. 2, it is clear that structural differences exist between the circuits within the boards. Using PEM3 error results in Table I, a vast difference between the numeric value of the highest and the lowest error is found. This is once again observed by comparing the results for Sample 7 to those of Sample 8, where the circuits with the most and least error are not the same. Circuit U4 in Sample8 can be considered the circuit that is most like all other circuits, or most like the board average because its total error is 1.245%. The total board error for Sample 8 (3.008%) using PEM3 is larger than the total error for Sample 7 (1.716% - not shown). Just like with the repeatability, it can be observed that on average the real impedance contributes the largest error in all cases.

C. Weighting Factor

The errors obtained for the real impedance are found to be quite influential in determining the overall errors for the various circuits and the boards. One way to combat this is to use a weighting factor to remove extreme outlier values. This is summarized in Table II. Since PEM1 and PEM2 give similar results, only PEM1 is included in Table II. Doing so allows us to compare the data for Sample 7 and Sample 8. It can be seen that each total percent error value has decreased substantially. For example PEM1 from Sample 8 (Θ) at U5, the total percent error reduces from 0.130% to 0.074%. The final board error for both samples also decreased for each circuit and property. The weighting factor had insignificant effects on the reproducibility results (PEM3). Although values were reduced at each circuit and property the changes were miniscule in comparison to that of the weighted repeatability results. This indicates that the current weighting method is only capable of filtering anomalous measurements made by the equipment and that differences observed are directly related to variabiity of the circuit patterns.

IV. CONCLUSION

Differences between the identical circuits on a board are quantifiable using various percent error methods selecting for repeatability or reproducibility. It was found that there is not a clear correlation between the circuits with the highest or the lowest error and their respective board locations. Material defects of the five circuits are found to play a role in determining the total percent error reproducibility values. The use of a weighting factor can play a significant role in removing anomalous data from repeatability results. Impedance measurements should be taken throughout a wider range of humidity levels to analyze its influence on the solder masked circuit boards. A sweep of measurements should also be taken over a range of temperatures. Methods for increasing sample repeatability will be tested by reducing operator error during measurements. Detailed quantification of the defects present on each of the circuit locations needs to be conducted so that it may be possible to find clear correlations between surface roughness parameters and the impedance responses of the five circuits in each board and establish a procedure for quantifying the quality of the uncoated boards. Additional work conducted on coated circuit boards is not included here but showed similar trends that need further study.

V. ACKNOWLEDGMENT

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VI. REFERENCES

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