SAND2022-0227C

Impedance Spectroscopy for Quality Testing of Interdigitated Circuits

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 factors, some of which include temperature and relative humidity of the environment of operation. When fabricating multiple identical components, it is important to ensure all variables involved in the fabrication of each component are equal. Impedance spectroscopy as a tool holds potential in 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 in quality testing two boards with interdigitated circuits fabricated at Sandia National Laboratory. Statistical methods are performed to share the referenceable numerical differences between the circuits on a board throughout the frequency range. It was found evident that significant differences existed between the circuits on a single board. Statistical methods were also able to test for both the equipment accuracy and production accuracy. Frequency was found to play a critical role in evaluating the impedance response of the circuits.**

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

I. Introduction

Impedance spectroscopy was used to characterize several solder masked circuit boards with interdigitated circuits fabricated at Sandia National Laboratory. Each circuit contain 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. These circuit boards were mainly categorized into coated and uncoated board. In this study two uncoated boards are investigated, Sample7 and Sample8. Uncoated boards were expected to have been fully shielded at the interdigitated combs before the application of the solder mask, however, this was not the case. This was observed with optical images taken using a PentaView LCD Digital Microscope. Shown in Fig. 2 are images of comb tips at the very edge of circuits U2 and U4. It was observed that various layers or regions existed on the circuits of the uncoated boards contrary to expectation, with the distinctive regions varying in size. It can also be noted that there are differences in surface roughness between the comb tips of U2 and U4. These differences exist within a circuit and across all circuits and will be quantified in more detail in the future.

Using impedance spectroscopy, it is possible to quantify the characteristic differences between the circuits on a single board and between multiple boards in terms of their impedance response. Measurements were done under normal laboratory conditions of relative humidity and temperature to represent sample responses under easily repeatable conditions. Investigated are the similarities and differences of the uncoated non-exposed boards in terms of statistical relations between measurements of a single circuit and measurements of all five circuits on two different boards.

II. Methods

A. Impedance Spectroscopy

Impedance measurements were done using a Solartron SI 1260 and Solartron 1296 Dielectric Interface, operated using SMaRT Impedance Measurement software. Measurements were done for the five circuits on each board. Three runs or tests were performed per circuit to verify the impedance response being measured, which were further reviewed using ZView Impedance Software. One such measurement spectrum is depicted in Fig. 3 for Sample8 at circuit U2. Measurements were performed at an AC voltage of 500 mV through a frequency

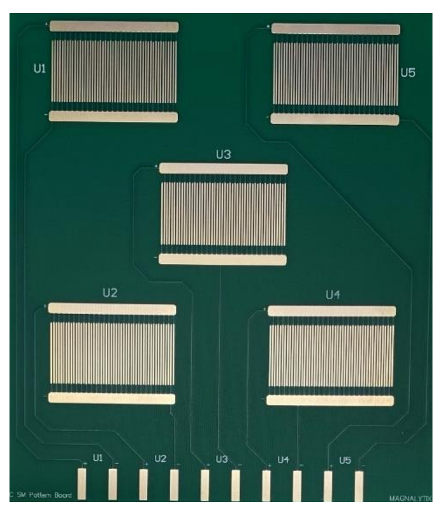

Fig. 1. Sample8 circuit board. Interdigitated circuit arrangement is equivalent for all boards, with their respective leads at the lower end in the order shown.

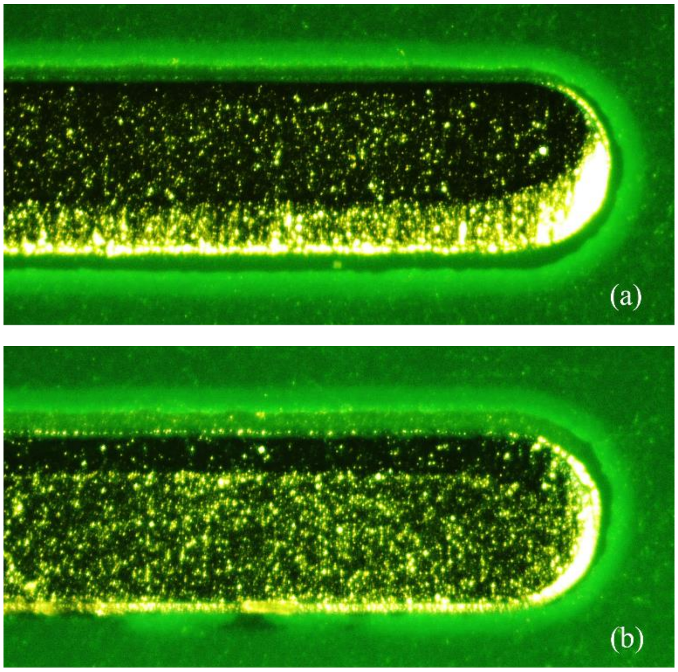

Fig. 2. Optical images of Sample8. Image 2a is a comb tip at circuit U2, 2b is a comb tip at circuit U4.

range of 100 mHz to 10 MHz at 15 steps per decade, with no DC voltage applied. Samples were placed in an ETS Humidity Chamber to have a controlled environment for relative humidity (RH), which was controlled using an ETS Dehumidifier Controller. Alligator clips were used on the leads of the circuit being measured on a board, connecting it to the 1296 Dielectric Interface. Each run performed measured the impedance response of the circuit as the impedance magnitude, phase angle, real, and imaginary, lasting approximately six minutes per run. After the three runs were performed, alligator clips were detached then transferred to the next circuit for measurement. Including time needed for attaching and detaching of the clips, total time spent fully measuring a sample (full board with all five circuits) at a particular humidity was approximately 120 minutes. This was done at 50% RH.

B. Statistical Methods

To produce numerical representations of the quality of the circuit boards, statistical methods were performed using MATLAB. Measurements were taken across the frequency range of 100 mHz to 10 MHz at 15 steps per decade, producing 121 data points for each of the four properties measured as the impedance response: impedance magnitude (ohms), phase angle (degree), real (ohms), and imaginary (ohms). Differences between measurements can then be quantified by comparing the respective properties of a single data point. Such comparisons are done per frequency level. Between the three measurements of a circuit an average, standard deviation, and percent error is calculated per frequency for each of the four properties. Average is performed using

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

where $\bar{x}$ is the circuit average, *x(i)* is the value of a property measured at run *i, n* is the total number of runs measured, and *x(i)* is summed from $i = 1$ to n, where $n = 3$. Standard deviation is performed using

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

where d is the standard deviation, $\bar{x}$ is the average, *x(i)* is the value of a property measured at run *i, n* is the total number of runs measured, and the quantity $|x(i) - \bar{x}|^2$ is summed from $i = 1$ to n, where $n = 3$. These calculations are done for the impedance magnitude ($\overline{Z}$), phase angle (Θ), impedance real (Z'), and impedance imaginary (Z") throughout the range of frequency used, or at each frequency level. This results in 121 values of the average and standard deviation for each property at each circuit measured. The three methods used to calculate the percent error can be separated into two categories: repeatability and reproducibility. Repeatability refers to measurement repeatability, 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. Greater similarities between circuit impedance responses would indicate the reproducibility of the production methods used in fabricating the circuits. Lower percent error value would indicate greater repeatability or reproducibility. Like that of the average and standard deviation, percent error calculations were also done per frequency level for each of the four properties measured. Two repeatability methods were used. In percent error method one (PEM1), repeatability is produced using the calculated average and standard deviation.

$$PEM1 = (d \,/\, |\bar{x}|) * 100 \qquad (3)$$

This results in a percent error value at each frequency level per property. In percent error method two (PEM2), repeatability is

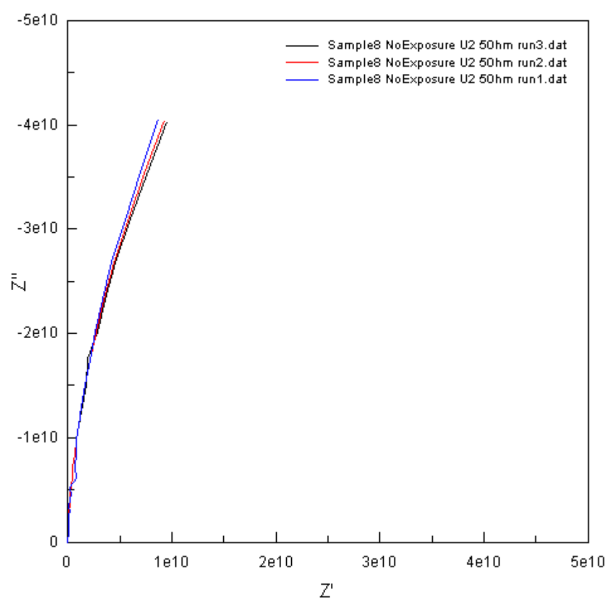

Fig. 3. Nyquist plots of Sample8 NoExposure board at the U2 circuit, where the three subsequent tests/runs are performed on the circuit. Taken from ZView software. Z' and Z" are in ohm units.

produced in two steps. First, a calculation for partial percent error is made with values from each individual run measured.

$$pPEM2(i) = \{|x(i) — \bar{x}| / |\bar{x}|\} * 100 \quad (4)$$

This is performed for each run, where $pPEM2(i)$ is the partial percent error of run i. Secondly, all the partial percent errors are averaged for all three runs.

$$PEM2 = \{\Sigma\, pPEM2(i)\} / n \quad (5)$$

The partial percent errors $pPEM2(i)$ are summed from $i = 1$ to n, where $n = 3$. This results in the percent error $PEM2$ at each frequency level per property. PEM2 is then performed for each circuit. Percent error method three (PEM3) is used to calculate reproducibility. Instead of circuit averages being compared with each individual run, PEM3 compares circuit averages with the board average. This is calculated by taking the mean of all five circuit averages per frequency and property

$$\bar{y} = \{\Sigma\, \bar{x}(j)\} / m \quad (6)$$

where $\bar{y}$ is the board average, $\bar{x}(j)$ is the circuit average per circuit j, m is the total number of circuits measured, and $\bar{x}(j)$ is summed from $j = 1$ to m, where $m = 5$. With the board average, partial percent error values can be calculated.

$$PEM3 = \{|\bar{x}(j) — \bar{y}| / |\bar{y}|\} * 100 \quad (7)$$

This is performed for each circuit, where $PEM3$ is the percent error of circuit j. This results in the percent error $PEM3$ per frequency and property, and PEM3 is then performed for each circuit from $j = 1$ to m, where $m = 5$.

It was decided that to have a referenceable value to represent either the repeatability or reproducibility, a summation of the percent errors would have to be calculated throughout the frequency range per property. This final value is referred to as the total percent error. This can be done for each of the percent error methods performed, resulting in three categories of total percent error: PEM1t, PEM2t, and PEM3t.

$$PEM1t = \{\Sigma\, PEM1(k)\} / l \quad (8)$$

As a function of frequency $PEM1(k)$ is the percent error at frequency k, l is the total number of frequency levels used, and $PEM1(k)$ is summed from $k = 1$ to l, where $l = 121$. Thus, $PEM1t$ is the total percent error from PEM1 throughout the entire frequency range of each impedance response property measured, resulting in four values of $PEM1t$ (|Z|, Θ, Z', and Z"). This calculation is performed for each of the four total percent error categories. After this, two more sets of means (or final errors) are calculated: one calculating the mean of the total percent errors of the four properties of a particular circuit; the other calculating the mean of the total percent errors of the total percent errors of all five circuits of a particular impedance property. The former produces a single value representative of the final error of a circuit, while the latter represents a single value representative of the final error of a property on the circuit board. When the former is performed, these values are representative of the final repeatability or reproducibility value of a circuit, and when the latter is performed these values represent the final repeatability or reproducibility value of an impedance response property of the circuit board.

Finally, a weighting factor is introduced with the goal of removing anomalous data before total percent errors are calculated. Recall that 121 points of frequency were used in taking the measurements, hence there are 121 percent error values per property of a circuit. For a given property and circuit, two frequency points of 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 error calculations are again performed.

III. Results

Three types of graphs are presented to represent the results of the analysis: single-circuit, multi-circuit, and board comparison graphs. Single-circuit graphs highlight differences between the three runs performed on a circuit. Multi-circuit graphs highlight differences between all five circuits of a board by plotting them together using the calculated average and standard deviation for the property being presented. Board comparison graphs highlight the differences between the impedance responses of the two boards. Nyquist plots graphing the Z" versus Z' are presented in Fig. 3 to 6 and are used to better highlight the differences observed graphically.

All circuits measured were found to exhibit capacitive behavior, highlighted by a constant reduction of the impedance magnitude as frequency increased. In the Nyquist plots presented, note that frequency is increasing from right to left along the curvature of the response. As the frequency used is reduced, the impedance response increases, resulting in the standard deviation growing larger towards low frequencies. This led to the use of percent error for numerically representing the differences between the runs and circuits measured.

A. *Repeatability*

As a measurement of equipment accuracy, repeatability of the measurements taken can be illustrated using single-circuit graphs. In Fig. 3, Sample8 at U2 is graphed with all three runs using ZView software. It is seemingly clear that measurements were repeatable as each run follows the same trend with a small spread of differences that are more evident at lower frequencies. To define this numerically, percent error methods PEM1 and PEM2 are used for repeatability. Table I holds the total percent error values derived from PEM1 for all circuits of Sample7, Table II derived PEM2 for Sample7, Table III derived PEM1 for Sample8, and Table IV derived PEM2 for Sample8. The values of the repeatability tables are considered the percent of irrepeatability of a particular circuit and property, highlighting the equipment accuracy in taking the measurements. Lower values hence indicate greater equipment accuracy and lower response irrepeatability.

Considering all repeatability tables, it was found that the impedance real of each circuit held the greatest error. This is likely due to the incomplete semi-circles produced in the nyquist plot, a trend shared by each circuit of the uncoated non-exposed boards. The Mean column represents the final error of each circuit and the board, hence used for comparisons between circuits and samples. For each sample, circuit of most and least error differed, while the results of both PEM1 and PEM2 can be seen to have good agreement with one another. The circuits of most and least error are:

- In Sample7, most error is found in U4, least error in U2.
- In Sample8, most error is found in U1, least error in U4.

This was the trend regardless of percent error method used. While U4 was found to have the most error in Sample7, U4 had the least error in Sample8. This helps to confirm that the repeatability of a circuit is not a function of its location on the board. Besides values of the impedance real and values of the circuit of most error on each sample, total percent error values are below 0.6%, exhibiting great repeatability. Even including the real impedance circuit of greatest error, values fall below 3.5%. With these tables, the Board row represents the final errors of the properties of the circuit board. When the average is taken from these values, the result is the final error of the board. This value can be used to compare the samples, in which it is shown that Sample7 has the lower error (where both PEM1 and PEM2 agree). Hence, Sample7 has the greater repeatability over all circuits and properties.

B. Reproducibility

As a measurement of circuit similarity, reproducibility of the measurements taken can be illustrated using the multi-circuit graphs like that of Fig. 4 and Fig. 5. In Fig. 4, all five circuits of Sample7 are graphed on a Nyquist plot using the calculated circuit averages and standard deviation. The same is done in Fig. 5 for Sample8. It is clear graphically that there are differences in the impedance response between the five circuits on a board. The reproducibility of a sample is affected by material defects. Referring to Fig. 2, it is clear structural differences exist between the circuits within boards. A board comparison graph can be made using the respective board average and standard deviation between all five circuit averages, performed on each board then graphed together. This is done in Fig. 6, where Sample7 and Sample8 board averages and standard deviations are graphed on a Nyquist plot. To define the reproducibility numerically, PEM3 is used. Table V holds the total percent error values derived from PEM3 for all circuits and properties of Sample7, and Table VI holds the total percent error for Sample8. PEM3 produces greater total percent error values due to the use of solely board and circuit averages. Like that of the repeatability tables, the circuits of most and least error can be observed from the reproducibility tables as:

- In Sample7, most error is found in U1, least error in U3.
- In Sample8, most error is found in U5, least error in U4.

Using PEM3 results, there is a vast difference between the numeric value of the circuit of most and least error. In Sample7's selection, most and least error circuits is not shared with that of its repeatability counterpart. In Sample8 however, circuit of least error is shared, being U4. In these tables, the derived values represent percent of material irreproducibility, where lower values indicate greater production accuracy and lower irreproducibility. Sample8's U4 can be considered the circuit that is most like all other circuits, or most like the board average. With that in mind, Fig. 4 and Fig. 5 helps in visualizing these similarities. Recall there are 121 points of frequency being used. Most of these data points are in high frequencies, which is representative of the increased clumping of the data points in the Nyquist plots moving from right to left of the response curvature (the direction of increasing frequency). The final error of both boards are calculated and presented in the same way as that of the repeatability tables. It is observed that Sample7 has a lower final board error (1.716%) than that of

TABLE I. SAMPLE7 TOTAL PERCENT ERROR DERIVED USING PEM1.

SD%	**Sample7: PEM1**				
	|*Z*|	***Θ***	***Z'***	***Z"***	***Mean***
U1	0.532	0.246	1.898	0.595	0.818
U2	0.067	0.043	0.951	0.069	0.283
U3	0.067	0.041	1.361	0.070	0.385
U4	0.131	0.158	3.079	0.130	0.874
U5	0.095	0.086	1.952	0.103	0.559
Board	0.178	0.115	1.848	0.193	0.584

TABLE II. SAMPLE7 TOTAL PERCENT ERROR DERIVED USING PEM2.

SD%	**Sample7: PEM2**				
	|*Z*|	***Θ***	***Z'***	***Z"***	***Mean***
U1	0.406	0.188	1.419	0.454	0.617
U2	0.050	0.032	0.714	0.051	0.212
U3	0.050	0.031	1.017	0.052	0.287
U4	0.099	0.121	2.339	0.099	0.664
U5	0.071	0.065	1.467	0.077	0.420
Board	0.135	0.087	1.391	0.146	0.440

TABLE III. SAMPLE8 TOTAL PERCENT ERROR DERIVED USING PEM1.

SD%	**Sample8: PEM1**				
	|*Z*|	***Θ***	***Z'***	***Z"***	***Mean***
U1	0.170	0.173	3.477	0.182	1.000
U2	0.107	0.110	2.629	0.120	0.742
U3	0.124	0.213	2.029	0.160	0.631
U4	0.049	0.055	1.042	0.058	0.301
U5	0.216	0.130	1.522	0.193	0.515
Board	0.133	0.136	2.140	0.143	0.638

TABLE IV. SAMPLE8 TOTAL PERCENT ERROR DERIVED USING PEM2.

SD%	**Sample8: PEM2**				
	|*Z*|	***Θ***	***Z'***	***Z"***	***Mean***
U1	0.128	0.128	2.623	0.136	0.754
U2	0.081	0.082	1.963	0.090	0.554
U3	0.094	0.161	1.521	0.121	0.474
U4	0.036	0.040	0.763	0.043	0.221
U5	0.165	0.098	1.142	0.146	0.388
Board	0.101	0.102	1.603	0.107	0.478

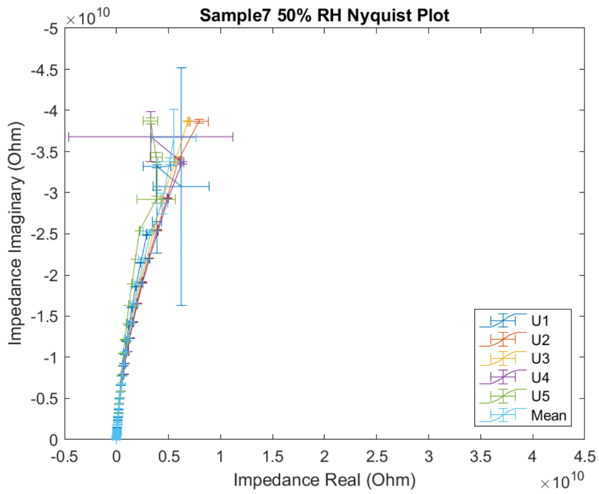

Fig. 4. Nyquist plots for all five circuits of Sample7 as well as board average (Mean). Plot produced using MATLAB.

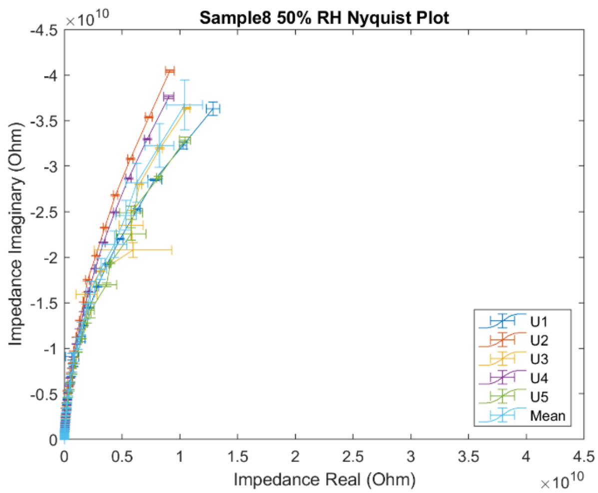

Fig. 5. Nyquist plot for all five circuits of Sample8 as well as the board average (Mean).

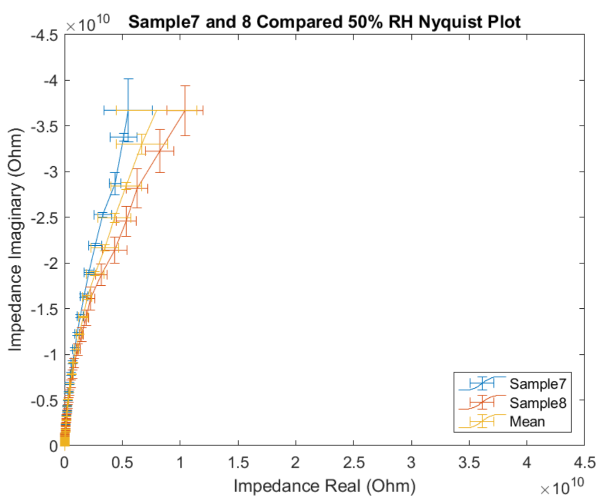

Fig. 6. Nyquist plots comparing the board averages with standard deviation of Sample7 and Sample8, accounting for all five circuits. Average of both boards (Mean) is also included with standard deviation.

Sample8 (3.008%). Just like in the repeatability tables, it can be observed that on average the impedance real has the most error.

C. *Weighting Factor*

In calculating the final circuit errors of a sample, the impedance real is significantly influential on the value produced. Hence the circuits found to be of least error may not truly be. To combat this, the weighting factor introduced in the methods is used. Two more repeatability tables are shared here to observe the effect of the weighting factor on Sample7 and Sample8. Because of the established agreeability between PEM1 and PEM2, these two tables solely use PEM1. Table VII holds the weighted total percent errors derived using PEM1 for Sample7, and Table VIII holds the weighted total percent errors derived using PEM1 for Sample8. The new weighted values indicate that the circuits of most and least error are:

- In Sample7, most error is found in U5, least error in U2.
- In Sample8, most error is found in U1, least error in U4.

The circuit with most error only changed for Sample7. Even more significant is the numerical reduction in error of Sample7 and Sample8. Each total percent error value is reduced, with many reducing by a factor of half, and a few reducing by an order of magnitude. This supports the idea that the removal of anomalous data will have major effects on the representative error of the samples, enough so to vary what is considered the circuit of most or least error. The final board error for both samples were also reduced by a substantial amount.

Two more reproducibility tables are shown to observe the effect of the weighting factor on PEM3. Table IX holds the weighted total percent errors derived using PEM3 from

TABLE V. SAMPLE7 TOTAL PERCENT ERROR DERIVED USING PEM3.

SD%	Sample7: PEM3				
	|*Z*|	*Θ*	*Z'*	*Z"*	*Mean*
U1	2.566	0.193	4.847	2.566	2.543
U2	1.070	0.164	3.772	1.063	1.517
U3	0.672	0.077	1.990	0.671	0.852
U4	1.435	0.231	5.095	1.429	2.048
U5	0.717	0.287	4.745	0.735	1.621
Board	1.292	0.191	4.090	1.293	1.716

TABLE VI. SAMPLE8 TOTAL PERCENT ERROR DERIVED USING PEM3.

SD%	Sample8: PEM3				
	|*Z*|	*Θ*	*Z'*	*Z"*	*Mean*
U1	2.413	0.279	4.738	2.374	2.451
U2	5.476	0.422	6.657	5.571	4.532
U3	1.517	0.167	3.826	1.543	1.763
U4	0.515	0.217	3.702	0.547	1.245
U5	6.840	0.370	6.084	6.903	5.049
Board	3.352	0.291	5.001	3.388	3.008

TABLE VII. SAMPLE7 WEIGHTED TOTAL PERCENT ERROR DERIVED USING PEM1.

SD%	Sample7: PEM1 (Weighted)				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*
U1	0.079	0.056	1.283	0.088	0.377
U2	0.055	0.025	0.760	0.058	0.224
U3	0.058	0.033	0.974	0.060	0.281
U4	0.057	0.034	1.020	0.059	0.293
U5	0.070	0.040	1.392	0.077	0.395
Board	0.064	0.038	1.086	0.068	0.314

TABLE VIII. SAMPLE8 WEIGHTED TOTAL PERCENT ERROR DERIVED USING PEM1.

SD%	Sample8: PEM1 (Weighted)				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*
U1	0.109	0.126	2.241	0.128	0.651
U2	0.085	0.084	2.019	0.098	0.572
U3	0.064	0.076	1.191	0.071	0.351
U4	0.039	0.044	0.946	0.048	0.269
U5	0.134	0.074	1.154	0.121	0.371
Board	0.086	0.081	1.510	0.093	0.443

TABLE IX. SAMPLE7 WEIGHTED TOTAL PERCENT ERROR DERIVED USING PEM3.

SD%	Sample7: PEM3 (Weighted)				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*
U1	2.420	0.111	4.278	2.408	2.304
U2	1.022	0.129	3.302	1.018	1.368
U3	0.626	0.062	1.709	0.622	0.755
U4	1.422	0.163	4.646	1.406	1.910
U5	0.683	0.220	4.205	0.683	1.448
Board	1.234	0.137	3.628	1.227	1.557

TABLE X. SAMPLE8 WEIGHTED TOTAL PERCENT ERROR DERIVED USING PEM3.

SD%	Sample8: PEM3 (Weighted)				
	|Z|	*Θ*	*Z'*	*Z"*	*Mean*
U1	2.375	0.207	4.214	2.342	2.285
U2	5.425	0.361	6.285	5.498	4.392
U3	1.494	0.105	3.262	1.507	1.592
U4	0.501	0.166	3.385	0.518	1.142
U5	6.760	0.330	5.774	6.821	4.921
Board	3.311	0.234	4.584	3.337	2.866

Sample7, and Table X holds the total percent error derived using PEM3 from Sample8. The weighting factor had insignificant effects on the reproducibility results. Selection for the circuit of most and least error remained the same. Total percent error values were reduced at each circuit and property, but the changes were miniscule, especially in comparison to that of the weighted repeatability results. This indicates that the current weighting method is only capable of filtering for anomalous measurements made by the equipment.

IV. CONCLUSION

Impedance spectroscopy is a useful tool for characterizing dielectric materials and electronic components. It was observed that differences can be found between the circuits on a single circuit board, which can be easily depicted with a Nyquist plot and quantified using various percent error methods revolving around repeatability or reproducibility. Repeatability is best depicted using single-circuit graphs, while Reproducibility is best depicted using multi-circuit graphs. It was found that there is not a clear correlation between the circuits of most or least error and their respective board locations. It is likely that material defects of the five circuits are playing a great role in the total percent error reproducibility values. The use of a weighting factor can play a significant role in sifting out the true representative total percent errors of a circuit and board, allowing for more accurate selection of circuits and samples of least error. The current method of weighting is simple but should be improved upon to seek out more optimized results without compromising the actual data. For now, weighting factor is only capable of significantly filtering out anomalous data involved with repeatability results.

Further impedance spectroscopy must be performed on these samples. Measurements were taken at normal laboratory conditions, with a humidity chamber controlling for a relative humidity of 50% RH. In future work, impedance measurements would be taken throughout a wide range of humidity levels to analyze its influence on the solder masked circuit boards. A sweep of measurements would also be taken over a range of temperature levels. Methods for increasing sample repeatability will be tested by reducing operator error during measurements. Equivalent circuit modeling of these samples must be done as well for use in simulating the behavior of the boards, which can aide in future design. Surface roughness of the five circuits on one of the uncoated non-exposed boards will be quantified and analyzed in hopes of finding clear correlations between surface roughness parameters and the impedance responses of the five circuits.

V. ACKNOWLEDGMENT

Sandia National Laboratory provided the solder masked circuit boards for characterization purposes. The authors thank M. Rath for help developing the model for uncoated samples (not shown). Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.