

PROGNOSTICATION FOR IMPENDING FAILURE IN LEADFREE ELECTRONICS SUBJECTED TO SHOCK AND VIBRATION USING RESISTANCE SPECTROSCOPY

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Abstract

Leading indicators of failure have been developed based on high-frequency characteristics, and system-transfer function derived from resistance spectroscopy measurements during shock and vibration. The technique is intended for condition monitoring in high reliability applications where the knowledge of impending failure is critical and the risks in terms of loss-of-functionality are too high to bear. The high-frequency characteristics, and system transfer function based on resistance spectroscopy measurements have been correlated with the damage progression in electronics during shock and vibration. Packages being examined include ceramic area-array packages. Second level interconnect technologies examined include copper-reinforced solder column, SAC305 solder ball, and 90Pb10Sn high-lead solder ball. Assemblies have been subjected to 1500g, 0.5 ms pulse. A positive prognostic distance has been demonstrated for each of the interconnect technologies tested.

Keywords: Prognostics, Shock, Vibration, Solder Joints, Reliability

Introduction

Damage diagnosis in high-reliability applications currently relies on the built in self test (BIST) to monitor for failure, focuses on reactive failure detection and provides limited insight into solder joint reliability and residual life. Previously, damage initiation, damage progression and residual life in the pre-failure space has been correlated with the micro-structural-damage based proxies, feature vectors based on time, spectral and joint time-frequency characteristics of electronics [Lall 2004, 2005, 2006^{a-c}, 2007^{a-d}, 2008^{a-f}]. Resistance spectroscopy measurements [Constable 1992, Lizzul 1994, Prassana 1995] have been used during thermal cycling tests to monitor damage progression due to thermo-mechanical stresses. The damage progression per cycle has been used to predict the number of cycles expected before failure based on the change in resistance of interconnects [Constable

2001]. Time-domain reflectometry coefficients have been used to isolate onset of damage under monotonic loading of a low-pass filter [Kwon 2008]. In this paper, the high-frequency characteristics, and system transfer function based on resistance spectroscopy measurements have been correlated with the damage progression in electronics during shock and vibration. Packages examined include ceramic and plastic area-array packages. Second level interconnect technologies examined include plastic-core solder ball, copper-reinforced solder column, SAC305 solder ball, and 90Pb10Sn high-lead solder ball. Assemblies have been subjected to 1500g, 0.5 ms pulse [JESD-B2111]. Continuity has been monitored in-situ during the shock test for identification of part-failure. Resistance spectroscopy based damage pre-cursors have been correlated with the optically measured transient strain based feature vectors. High speed cameras have been

used to capture the transient strain histories during shock-impact. Statistical pattern recognition techniques have been used to identify damage initiation and progression and determine the statistical significance in variance between healthy and damaged assemblies. Models for healthy and damaged packages have been developed based on package characteristics. It has been shown that high-frequency characteristics and system-transfer characteristics based on resistance spectroscopy measurements can be used for condition-monitoring, damage initiation and progression. A positive prognostic distance has been demonstrated for each of the interconnect technologies tested.

Test Vehicle

Two test boards were used for experimental measurements. Test board A, was manufactured in four different configurations. The boards have daisy-chained ceramic packages with 400 I/O each. Each test board has 8-packages on one side of the test board. All packages on test-board A have the same interconnect type. Interconnect technologies studied include, Cu-reinforced solder column grid array (CCGA), Eutectic tin-lead solder (63Sn37Pb), high lead solder (Sn10Pb90) and SAC305 solder (Sn3Ag0.5Cu). Table 1 shows the package parameters for test board A. A representative board with each package numbered U1 – U8 is shown in Figure 1.

Table 1: Package Architectures for Test Board A

Parameter	CCGA Columns	CBGA 63Sn37Pb	CBGA Sn10Pb90	CBGA Sn3Ag0.5Cu
Length (mm)	21	21	21	21
Width (mm)	21	21	21	21
Thick (mm)	2.4	2.4	2.4	2.4
I/O	400	400	400	400
Pitch (mm)	1	1	1	1
Ball Dia (mm)	0.6	0.6	0.6	0.6
Joint Ht (mm)	2	0.6	0.6	0.6

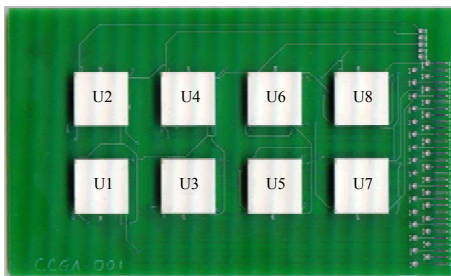


Figure 1: Test Board A

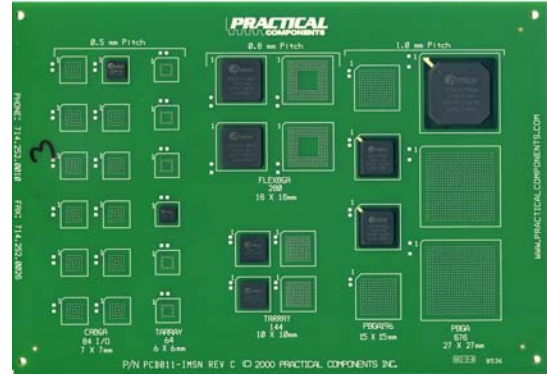


Figure 2: Test Board -B

Table 2: Package Architectures for Test Board B.

	6 mm Tape Array	7 mm Chip Array	10 mm Tape array	15 mm PBGA	16 mm Flex BGA	27 mm PBGA
I/O	64	84	144	196	280	676
Pitch (mm)	0.5	0.5	0.8	1	0.8	1
Die Size (mm)	4	5.4	7	6.35	10	6.35
Substrate Thick (mm)	0.36	0.36	0.36	0.36	0.36	0.36
Pad Dia. (mm)	0.28	0.28	0.30	0.38	0.30	0.38
Substrate Pad	NSMD	NSMD	NSMD	SMD	NSMD	SMD
Ball Dia. (mm)	0.32	0.48	0.48	0.5	0.48	0.63

Test Board-B includes package architectures such as, plastic ball-grid arrays, chip-array ball-grid arrays, tape-array ball-grid arrays, and flex-substrate ball-grid arrays (Figure 2). The experimental matrix has ball counts in the range of 64 to 676 I/O, pitch sizes are in the range of 0.5mm to 1mm, and package sizes are in the range of 6mm to 27mm (Table 2). The package parameters of this board are shown in Table 2. Representative samples of the test board B is shown in Figure 2.

Resistance Spectroscopy Approach

Leading indicators of damage have been developed based on resistance spectroscopy and impedance response phase shift of interconnects. The interconnect impedance response has been measured as a function of input signal frequency during shock and vibration. Two-stage phase sensitive detection has been used for measurement of the resistance

change and phase change. The experiment is excited at a fixed frequency from a function generator and the response from the experiment is detected at the reference frequency. The reference signal, $V_L \sin(\omega_L t + \theta_{ref})$, is obtained as sync output from a function generator, and is a sine wave at frequency ω_L . The response from the experiment can be represented by $V_{sig} \sin(\omega_r t + \theta_{sig})$ where V_{sig} is the signal amplitude. The signal is amplified and then multiplied by the reference using a phase-sensitive detector or multiplier [SRS 2006]. The output of the PSD is the product of two sine waves:

$$\begin{aligned} V_{psd1} &= V_{sig} V_L \sin(\omega_r t + \theta_{sig}) \sin(\omega_L t + \theta_{ref}) \\ &= \frac{1}{2} V_{sig} V_L \cos[(\omega_r - \omega_L)t + (\theta_{sig} - \theta_{ref})] \\ &\quad - \frac{1}{2} V_{sig} V_L \cos[(\omega_r + \omega_L)t + (\theta_{sig} + \theta_{ref})] \end{aligned} \quad (1)$$

The phase-sensitive detection output contains two AC signals, one at the difference frequency $(\omega_r - \omega_L)$ and the other at the sum frequency $(\omega_r + \omega_L)$. The reference signal is adjusted such that reference frequency equals the experimental output frequency, $\omega_r = \omega_L$. The output is passed through a low pass filter, the AC signals at frequency $(\omega_r + \omega_L)$ are removed. Output of the low-pass filter is a DC signal represented by

$$V_{psd1} = \frac{1}{2} V_{sig} V_L \cos(\theta_{sig} - \theta_{ref}) \quad (2)$$

$$V_{psd1} \propto V_{sig} \cos \theta$$

Where, V_{psd1} is output from first phase sensitive detector, θ is the phase difference between experiment signal and reference oscillator signal. Output of the first phase-sensitive detector is proportional to phase difference. The phase dependency has been eliminated by using a second phase-sensitive detector. The signal has been multiplied with the reference oscillator shifted by 90° , i.e., $V_L \sin(\omega_L t + \theta_{ref} + 90^\circ)$, using a second phase-sensitive detector. The output has been passed through a low-pass filter.

$$V_{psd2} = \frac{1}{2} V_{sig} V_L \sin(\theta_{sig} - \theta_{ref}) \quad (3)$$

$$V_{psd2} \propto V_{sig} \sin \theta$$

Where, V_{psd2} is output from second phase sensitive detector, θ is the phase difference between experiment signal and reference oscillator signal. The two phase-sensitive detectors result in two outputs, one proportional to $\cos\theta$, and the other proportional to $\sin\theta$. The outputs are represented with X and Y:

$$\begin{aligned} X &= V_{sig} \cos \theta \\ Y &= V_{sig} \sin \theta \end{aligned} \quad (4)$$

The phase dependency is removed by computing the signal resultant. The use of the technique for prognostication of shock and vibration induced damage is new. An AC Wheatstone bridge has been used in conjunction with a lock in amplifier that measures the magnitude and phase shift of the signal. The work presented in this paper utilizes the phase shift of the signal output from the AC bridge instead of the magnitude of the signal. The setup is shown in Figure 3. Two capacitors have been added to the bridge balancing resistors and the constant voltage source replaced with a signal generator. The daisy chained package has been denoted by the acronym, PKG in Figure 3. A change in package resistance will produce a change in the magnitude and phase shift of the output signal.

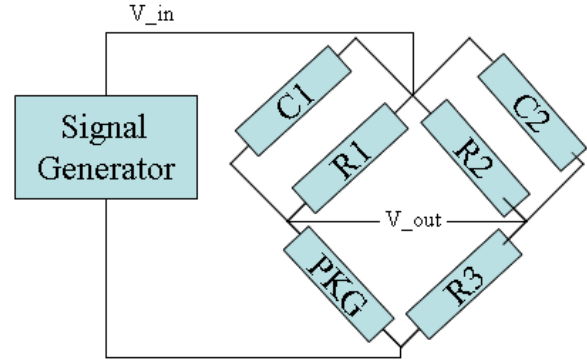


Figure 3: Wheatstone Bridge with capacitors C1, C2 and resistors R1, R2, R3, PKG

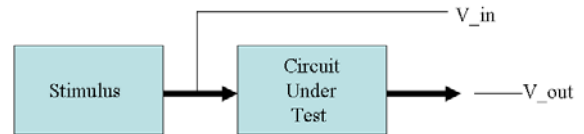


Figure 4: Inputs and outputs for resistance spectroscopy setup

The driving frequency of the input signal has been swept in the frequency range of 1 Hz to 1 MHz to measure damage initiation and progression due to shock and vibration. The bridge response has been measured for both magnitude and phase (Figure 4). Figure 5 shows the theoretically expected behavior from the resistance change in interconnects of the package due to damage accrued during shock and vibration system. Figure 5 shows that the magnitude of the output signal increases with a positive change in resistance. In addition, it also been shown that the phase shift of the output signal in the 10kHz to 10MHz range will change as the resistance of the package changes due to accrued damage. Figure 6 shows a superposition of the theoretically calculated

phase shift and the experimentally observed phase shift of a healthy package. It is believed that data at the high end of the frequency range starts to be dominated by high frequency characteristics such as the skin effect and deviates from the theoretically predicted model.

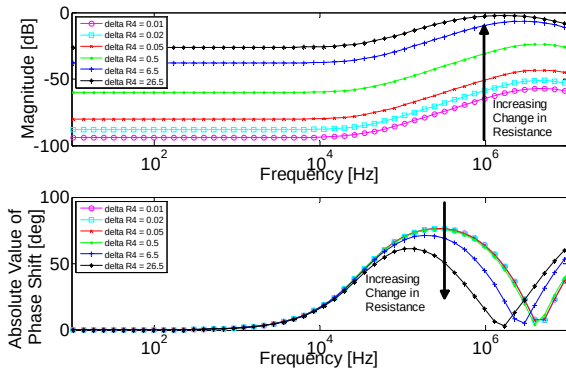


Figure 5: Bode Plots of Theoretical Transfer function. Arrows indicate trends of increasing resistance of the package

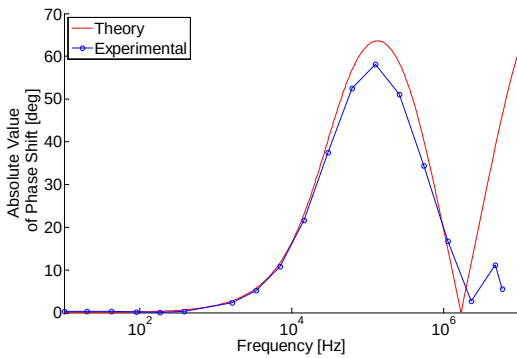


Figure 6: Comparison of theoretically derived transfer function and experimentally measured results for a healthy package (Test Board A, SAC alloy, Package U1).

Experimental Setup

The test assemblies were mounted face down on a Lansmont Model 23 drop tower and subject to a 0.5 millisecond, 1500G impact pulse in accordance with JEDEC standard JESD-B211 (Figure 7). Continuity for damage detection was done during the drops. Electrical continuity was monitored at 10 million samples per second during the test. High speed digital video for use with digital image correlation software was also recorded during the drop test. The boards were subjected to resistance spectroscopy including both magnitude and phase-shift measurements between drops.

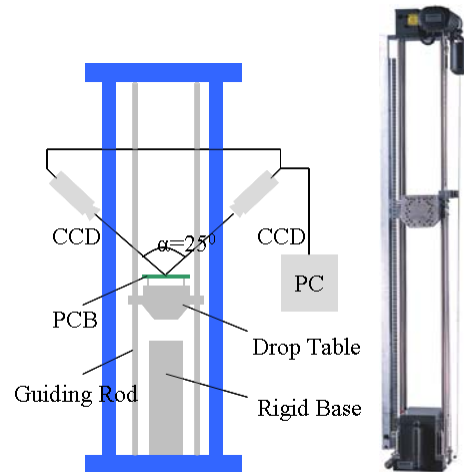


Figure 7: (a) Drop tower and high speed digital cameras for digital image correlation (b) Lansmont Model 23 Shock Test System

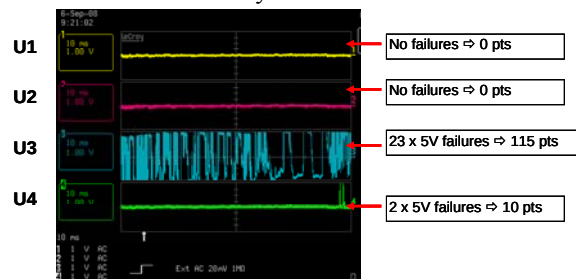


Figure 8: Failure Metric Calculation from Electrical Continuity.

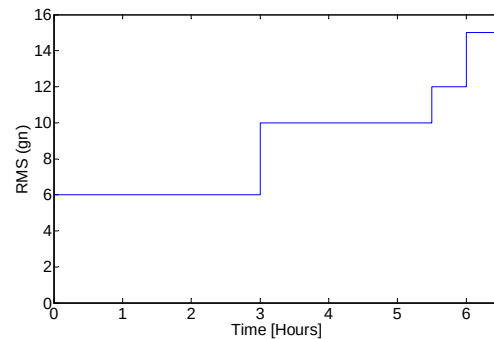


Figure 9: Step stress profile for vibration testing

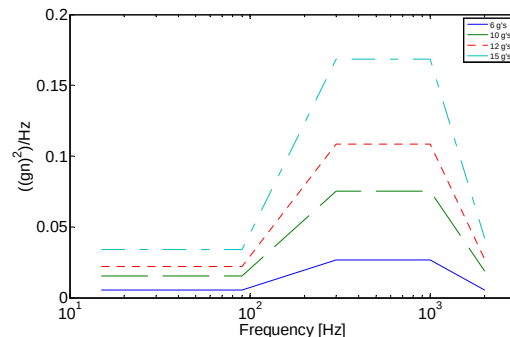


Figure 10: Random vibration profile at varying g levels

Phase shift measurements were repeated between drops until all packages on the board failed. The packages show varying degrees of damage when electrical continuity failures occur. A metric has been created to quantify the damage sustained by the packages. Figure 8 shows how the number of open events, multiplied by the severity of the event to arrive at a point system quantifying the severity of the failure. Each package is interrogated by the resistance spectroscopy technique individually. Switching has been used to cycle through all the packages on the test board. In addition to shock, the test assemblies were subjected to vibration testing on a LDS Model V722 vibration table. A step stress profile was used to gradually ramp up the stress level to induce damage (Figure 9). The individual random stress profiles used in the step stress are shown in Figure 10.

Training Signal and Onset of Failure

Each measurement data-set has been processed for measured magnitude of the output signal and the phases shift with respect to the input signal. The phase shift of the output signal from the Wheatstone bridge at has been measured at 19 different frequencies. At each frequency a sample size of 200 data points has been recorded. Figure 11 shows the bode plot of the healthy package. Bode plots have been constructed for each package on the test board after each drop and finite time increments during vibration.

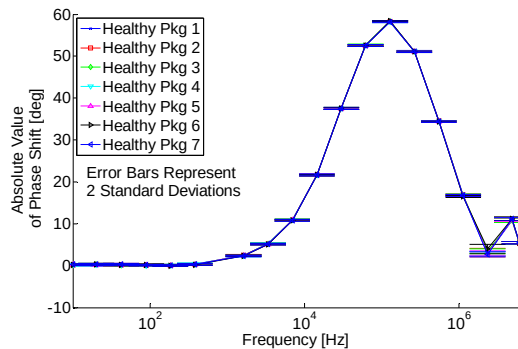


Figure 11: Repeatability of phase shift measurement on healthy packages (Test Board-A, SAC alloy)

A training data-set has been constructed for healthy packages on the test assemblies. Variation in the transient data set for healthy assemblies and the deviation from the training data set in the damaged assemblies has been quantified using the t-statistic. Figure 11 shows the repeatability of the phase shift measurement for healthy packages at different locations on the same board. The data for the healthy pristine configuration of a package is used as a baseline for the confidence value calculation. The

deviation in the magnitude and phase shift characteristic has been monitored from pristine state to a damaged state prior to failure, and eventual failure.

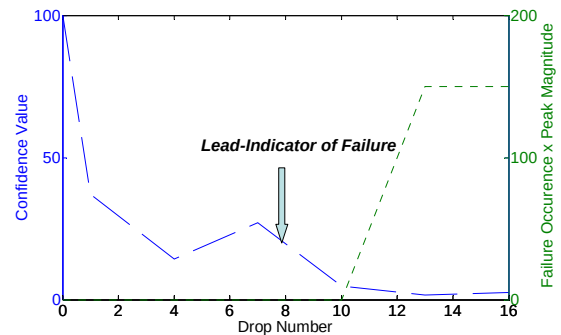


Figure 12: Confidence value as a lead indicator of failure during a drop test (Test Board-B, PBGA676)

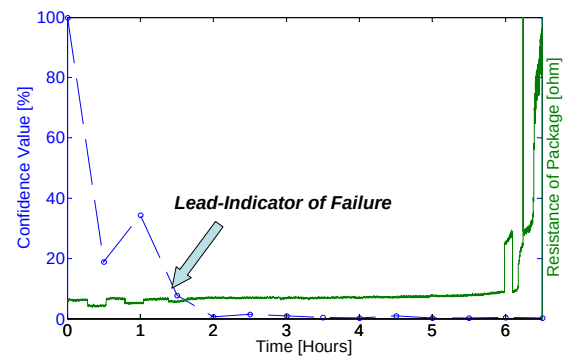


Figure 13: Phase shift as a lead indicator of failure (Test Board-B, PBGA676, 127kHz)

Figure 12 shows the confidence value based on phase shift measurements of a package versus number of shock events in order to determine the statistical significance of the phase shift at a single frequency with respect to its original baseline healthy configuration. The confidence value degradation has been overlaid with the failure metric defined as the number of open events multiplied by the severity of the event to arrive at a point system quantifying the severity of the failure. A higher failure metric value implies the number and severity of electrical opens is increasing. The failure metric indicates that the package failed electrical continuity in the neighborhood of twelfth drop. Degradation in the confidence value precedes failure in the package interconnects. The correlation of the decrease in confidence value as a leading indicator of failure is not identical for all of the frequencies used in this experiment. In this plot only data measured at input signal frequency of 127kHz is displayed. A similar trend in the degradation of confidence value for use as a leading indicator of failure can be shown during a vibration test as in Figure 13.

Prognostic Distance

A prognostic distance metric has been used for analyzing the damage proxy's ability for use as a leading indicator of failure. Statistical significance of phase shift with respect to the training signal has been used as one of the leading indicators of failure. Prognostic distance is defined as the lead-time between the indication of impending failure and electronic assembly failure. For shock-loads the prognostic distance has been measured in number of shock events. Impending failure is indicated by degradation in the confidence value that damage proxy in current assembly configuration is identical to that in the pristine undamaged assembly. Table 3, Table 4, Table 5 show the prognostic distances measured on various interconnect systems in a shock environment at input signal frequencies of 127 kHz, 2.33 MHz, 6MHz respectively. Prognostic distance has been determined using threshold value of confidence value degradation.

Table 3: Prognostic Distance (Board A, 127kHz)

Interconnect Type	Frequency (kHz)	Threshold Confidence Value (%)	Number of Samples	Average Prognostic Distance (No. of Drops)	Std. Deviation (No. of Drops)	False Positives
SAC305	127	90	3	6.33	3.06	0
63Sn37Pb	127	90	4	24.75	8.62	0
90Pb10Sn	127	95	6	18.67	6.02	0
Cu-CCGA	127	30	4	41.5	9.47	0

Table 4: Prognostic Distance (Board A, 2.33MHz)

Interconnect Type	Frequency (MHz)	Threshold Confidence Value (%)	Number of Samples	Average Prognostic Distance (No of Drops)	Std. Deviation (No of Drops)	False Positives
SAC305	2.33	50	3	8.33	5.03	0
63Sn37Pb	2.33	70	4	23.75	13.43	0
90Pb10Sn	2.33	85	6	18.17	10.65	0
Cu-CCGA	2.33	30	4	22.75	10.9	0

Table 5: Prognostic Distance (Board A, 6MHz)

Interconnect Type	Frequency (MHz)	Threshold Confidence Value (%)	Number of Samples	Average Prognostic Distance (No of Drops)	Std. Deviation (No of Drops)	False Positives
SAC305	6	35	3	9	4	0
63Sn37Pb	6	20	4	18.75	4.65	0
90Pb10Sn	6	25	6	13.17	9.85	0
Cu-CCGA	6	30	4	43.5	23.39	0

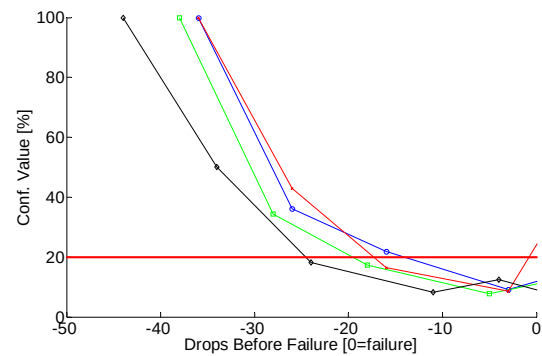


Figure 14: Determination of prognostic distance using a threshold value shown in red. Each trace is an individual package. (Test Board-A, SAC305 alloy) (Test Board-A, CBGA Package U2, $f = 6\text{MHz}$)

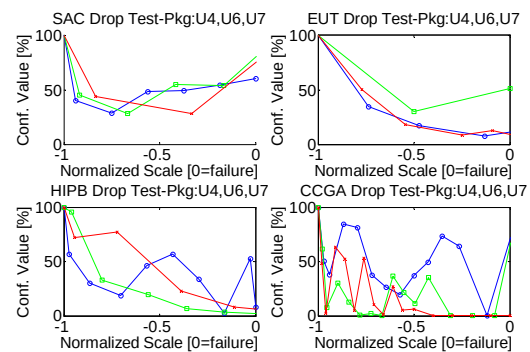


Figure 15: Degradation of CV during drop test on a normalized scale. U4 is shown with blue circles, U5 is shown with green squares and U6 is shown with red crosses (Test Board-A, 6MHz)

The prognostic distance is positive in all cases with no false positives measured in any configuration examined. The positive prognostic distance indicates that the damage proxy significantly precedes catastrophic failure of the package interconnects. Table 3, Table 4, Table 5 illustrate the trade off between the prognostication distance and

likelihood of a false positive. The prognostic distance is the highest for the 2.33 MHz input frequency, however the likelihood of false positives is also the largest indicated by the larger standard deviation.

The prognostic distance is the smallest for the 6MHz input signal, however the propensity of false positives is also the smallest indicated by the smaller standard deviation. For high reliability electronic applications false positives are completely unacceptable and therefore the system would be designed to avoid that type of error. Figure 14 shows the confidence value degradation preceding failure and the confidence value threshold for SAC305 interconnects. Zero drops on the x-axis in Figure 14 indicates the time when failure of the electronic assembly was detected. The significant degradation in statistical confidence values indicates that the impending failure can be detected before failure of the electronic assembly. The aggressive threshold value has been chosen to achieve statistical significance of difference to minimize occurrence of false positives. Figure 15 shows the repeatability of the confidence value degradation trend for various interconnect types including the SAC305, 63Sn37Pb, 90Pb10Sn, and Cu-CCGA. The graphs show good repeatability. In each case, the degradation in confidence value significantly precedes failure exhibiting the ability of the damage proxy to serve as the leading indicator of failure. The difference in the degree of monotonic degradation is expected because of differences in the failure manifestation in the different interconnect systems. A threshold value of 20-percent has been used to signify impending failure and calculation of prognostic distance.

Failure Modes

Package failure modes have been verified with x-sectioning of the samples after failure. Several failure modes in the second interconnects have been observed. These include, trace cracking, solder interconnect failure in bulk or at the interfaces, and pad cratering. Figure 16 and Figure 17 show representative failures for all interconnect types on test board A.

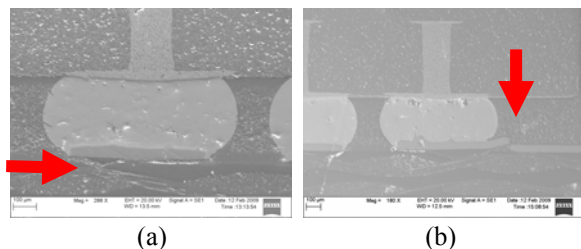


Figure 16: (a) Damaged SAC Joint (b) Broken trace on EUT (Test Board A)

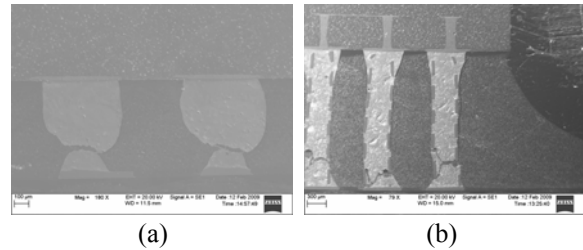


Figure 17: (a) Cracks through HIPB (b) Failed CCGA interconnect (Test Board A)

Conclusions

A new technique has been developed for prognostication of second-level interconnect failures in electronic assemblies. The technique is based on damage pre-cursors derived from phase shift of the measured frequency response of the electronic assemblies using resistance spectroscopy measurements during shock and vibration. Package architectures studied include ceramic area-array packages with multiple different second level interconnects including 63Sn37Pb, SAC305, copper reinforced solder columns, and 90Pb10Sn solder interconnects, plastic and flex-substrate ball grid array packages. Resistance spectroscopy based damage precursors have been measured during 1500g, 0.5ms shock and step-stress random vibration profiles. Data on eventual failure of the electronic assemblies has been gathered with high speed data-acquisition systems. Existence of positive prognostic distances for the various interconnect structures exhibits that the presented techniques can be used for early detection of impending failure in electronic assemblies. The trade-off between prognostic distance and the propensity of false positives has also been examined and shown to have an inverse relationship. The failure modes have been studied in the packages after failure.

Acknowledgements

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