Detection of Solder Joint Degradation Using RF Impedance Analysis

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Abstract

The trend for many types of electronic products is toward higher operating frequencies or digital bit rates. At high frequencies, signal propagation is concentrated at the surface of interconnects, a phenomenon known as the skin effect. Degradation of interconnects, such as cracking of solder joints due to fatigue or shock loading, also usually initiates at the surface and propagates inward. Therefore, even a small crack at the surface of a solder joint may affect the performance of high speed electronic assemblies. Traditional DC resistance measurements are not appropriate for detecting such a small fault. More accurate and sensitive alternatives are required for monitoring the reliability of current and future electronic products. RF impedance analysis offers an improved means of sensing interconnect degradation.

This study demonstrates the use of RF impedance changes as an early indicator of physical degradation of solder joints, due to the skin effect, and compares this to DC resistance measurements. Mechanical shear tests at an elevated temperature have been conducted with an impedance-controlled circuit board on which a surface mount component was soldered. Simultaneous measurements were performed of DC resistance and the time domain reflection coefficient, as a measure of RF impedance, while the solder joints were stressed. The RF impedance was observed to increase in response to cracking of the solder joint earlier than the DC resistance. These results were qualitatively repeatable over multiple trials.

Introduction

As clock speeds and communication frequencies rise, the performance and reliability of electronic products are becoming increasingly sensitive to the integrity of the interconnects across which signals travel. Common interconnects include solder joints, printed circuit board traces, and connectors. These interconnects are susceptible to fatigue failures, which are generally initiated by cracks in the circumferential area where the strain range is maximized, and propagate inward [1-4].

At high operating frequencies, the signal propagation is concentrated at the surface of interconnects. This phenomenon is known as the skin effect. The skin depth refers to the thickness of the conductor within which approximately 63% of the signals is contained [5]. As shown in equation (1), the skin depth, δ, is directly related to the frequency, f, and the resistivity of the conductor, ρ:

$$\delta = \sqrt{\frac{\rho}{f\pi\mu_0}} \tag{1}$$

where μ_0 denotes the material's permeability in a vacuum.

Signal propagation in high frequency electronic assemblies is more sensitive to mechanical degradation of interconnects than it is in low frequency electronic assemblies due to surface concentration. In other words, even a small crack at the surface of an interconnect can directly influence signal integrity, which may reduce the performance of high speed electronic products. In monitoring interconnect reliability for high speed applications, traditional low speed measurements, such as DC resistance, are of limited value since they are not able to sense partial cracks that can affect the performance of high speed assemblies. As a reliability monitoring tool, DC resistance often responds too late, for example, after the crack is large enough to result in a DC open circuit. RF impedance, however, should be capable of detecting small cracks. Due to the skin effect, RF impedance should show an increase in response to physical degradation at the surface earlier than DC resistance. Figure 1 shows a conceptual representation of the increased sensitivity of RF impedance measurements to physical degradation of interconnects.

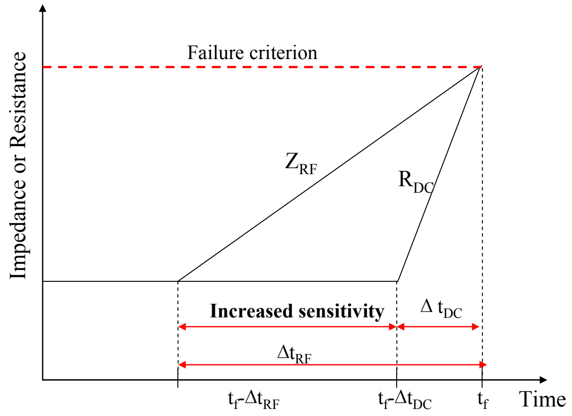

Figure 1 – Conceptual representation of increased sensitivity of RF impedance to interconnect degradation

In this study, shear stresses at the elevated temperature were used to cause solder joint degradation. The simultaneous measurement of RF impedance and DC resistance allowed a direct comparison of their sensitivities in detecting physical degradation of solder joints.

Solder joint degradation measurement

Impedance is a measure of the overall opposition of an electrical circuit to an alternating current at a given frequency [6]. It has three components: resistance, inductive reactance, and capacitive reactance. Resistance depends on the physical properties and dimensions of the conductor such as the resistivity of the material, the length and cross-sectional area.

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The signal frequency affects the resistance because at high frequency the effective cross-sectional area of the conductor is reduced due to the skin effect. Reactance also depends on the frequency. Inductive reactance is proportional to the signal frequency, whereas capacitive reactance is inversely proportional to the frequency. Based on these relationships, the frequency range of an impedance measurement can be chosen in order to capture a desired set of attributes of the circuit.

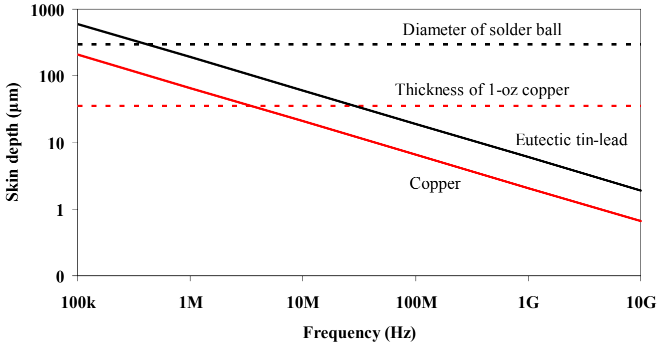


Figure 2 – Comparison between skin depth and interconnect dimensions

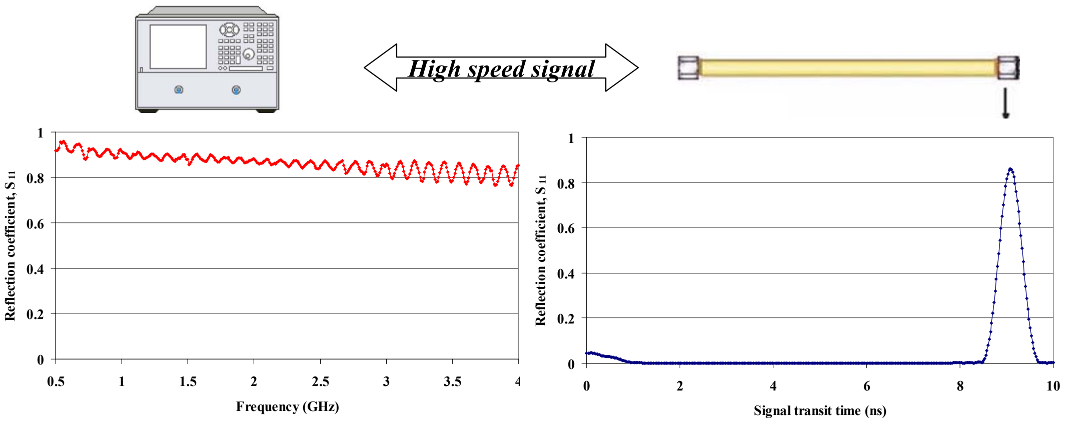


Figure 3 – Frequency domain analysis vs. time domain analysis

In order for impedance to exhibit enhanced sensitivity to interconnect degradation, the skin depth should be less than the interconnect thickness. Figure 2 describes the relationship between the frequency and the skin depth for 1-oz copper and eutectic tin-lead solder compared to typical dimensions of these two kinds of interconnects. According to Figure 2, the skin depth for both copper and eutectic tin-lead becomes less than about a tenth of the interconnect thickness above approximately 500MHz. Since many commercial products are currently operating in the frequency range of a few gigahertz, in this study the monitored frequency window was chosen to be 500 MHz to 4 GHz.

In high frequency applications, S-parameters are commonly used to characterize electrical performance. S-parameters can be measured by using a network analyzer to send high speed signals through the circuit and measure reflection (S_{11}, S_{22}) and transmission (S_{21}, S_{12}) coefficients over either the frequency or time domain. A frequency domain measurement shows the effect of discontinuities present in the circuit as the amplitude of the reflected (S_{11}) or transmitted (S_{21}) signal across the frequency spectrum, although this measurement does not directly provide spatial localization of the discontinuities. On the other hand, a time domain measurement shows any discontinuities as discrete peaks with respect to their position in the circuit. This is useful in identifying fault locations. Figure 3 offers a comparison between frequency and time domain analysis. Since this study focuses on the solder joint degradation that occurs at specified locations in the circuit, a time domain analysis was conducted.

The independent variable, or x-axis, of the time domain plot, is the round-trip transit time for electrical signals from the network analyzer port to a particular location on the circuit. The signal will propagate at close to the speed of light. Therefore, the distance from a reference point (the end point where calibration has been conducted) to the peak location may be calculated by multiplying the speed of the electrical signal by half the measured signal transit time. In this study, signal transit time values are reported directly because locations of features of interest, such as solder joints, are readily identifiable.

The dependent variable, or y-axis, of the time domain plot is the time domain reflectometry (TDR) reflection coefficient, which is essentially a ratio of the reflected power of the signal sensed at a port to that of the transmitted signal from the same port. A solder joint can be characterized by monitoring the reflection coefficient at the joint due to impedance discontinuities. The reflection coefficient is effectively equivalent to the S_{11} measurement; however, the time domain measurement is a composite response of all the frequencies monitored. The TDR reflection coefficient can range from -1 to 1, and may be conveniently reported in milliunits (mU).

Experimental setup

A test circuit for simultaneous measurement of the RF and the DC response has been developed, as shown in Figure 4. The test circuit consists of the following: an impedance-controlled board with an SMT low pass filter, two bias-tees, RF cables, mechanical load unit, and measurement instruments. The board has a controlled characteristic impedance of 50 Ohms to match that of the test equipment, cables, and other components. A surface mount low pass filter was soldered to this circuit board,. The cut-off frequency of the low pass filter is 6.7 GHz. Since the monitoring frequency range in this study is between 500 MHz and 4 GHz, the filter acts as a conductor with the same characteristic impedance of 50 Ohms.

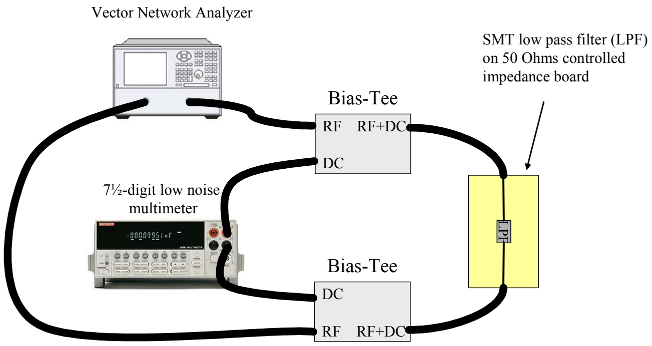


Figure 4 – Schematic of the circuit for simultaneous monitoring of the RF and the DC responses

In order to allow simultaneous monitoring of the RF impedance and the DC resistance, bias-tees were incorporated into the test circuit. The DC and the RF measuring instruments were connected to the DC and the RF ports of the bias-tees, respectively, while the composite ports were connected to both ends of the circuit board. All connections were made using RF cables, which also had a characteristic impedance of 50 Ohms.

As seen in Figure 4, a Keithley 2010 7.5 digit multimeter and an Agilent E8364A vector network analyzer (VNA) were used to monitor the DC resistance and the RF impedance, respectively. The VNA had a frequency range of 45 MHz to 50 GHz and was configured with TDR functionality. Both instruments were externally monitored to allow automated data acquisition.

Test conditions

Figure 5 shows the experimental setup for the shear test. Mechanical shear force was directly applied to the low pass filter to degrade the solder joints connecting the filter to the circuit board. A ceramic (Al_2O_3) material was inserted to prevent electrical contact between the metal tip of the mechanical loading fixture and the low pass filter. An initial displacement of the tip generated an applied force which was less than the over-stress level for the solder joints. The temperature was maintained at 150 ^oC using a ThermoStream. Both the RF and the DC responses were collected every 10 seconds.

Instrument control software was used to collect the DC resistance measurements periodically. At the same time, the TDR reflection coefficients over the entire time domain of the test circuit were collected. For comparison, the TDR reflection coefficients from the failure site were extracted and displayed in the same plot as the DC resistance measurements. The actual values of initial TDR reflection coefficient and DC resistance depend on the amount of solder and vary somewhat from sample to sample, although similar trends were observed in multiple experimental trials. Each experiment was conducted until it resulted in a DC open circuit.

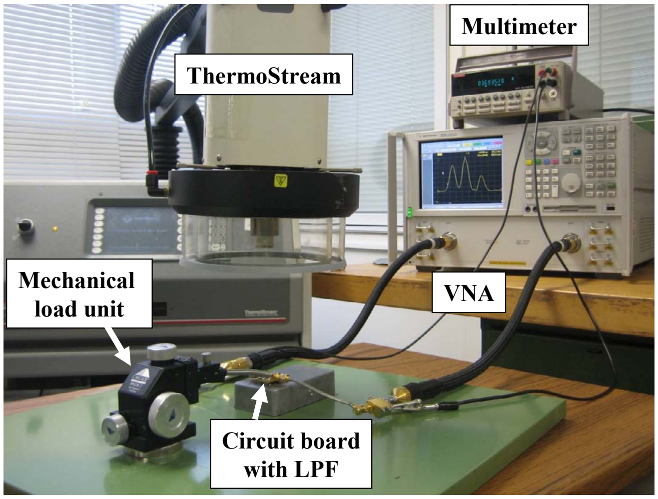


Figure 5 – Experimental setup for the shear test

Results and discussions

The TDR reflection coefficients at specific points of interest were extracted from the time domain data. Figure 6 shows two measurements of TDR reflection coefficient over the signal transit time domain, one taken before and the other after the experiment. As seen in the figure, three major peaks were observed. Peaks from left to right indicated impedance mismatches in the connector of the first bias-tee, the component with solder joints, and the connector of the other bias-tee, respectively.

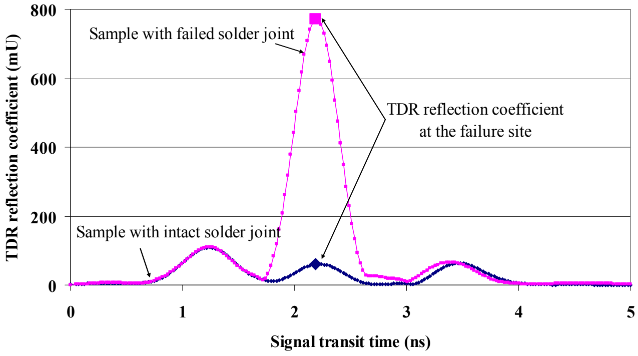
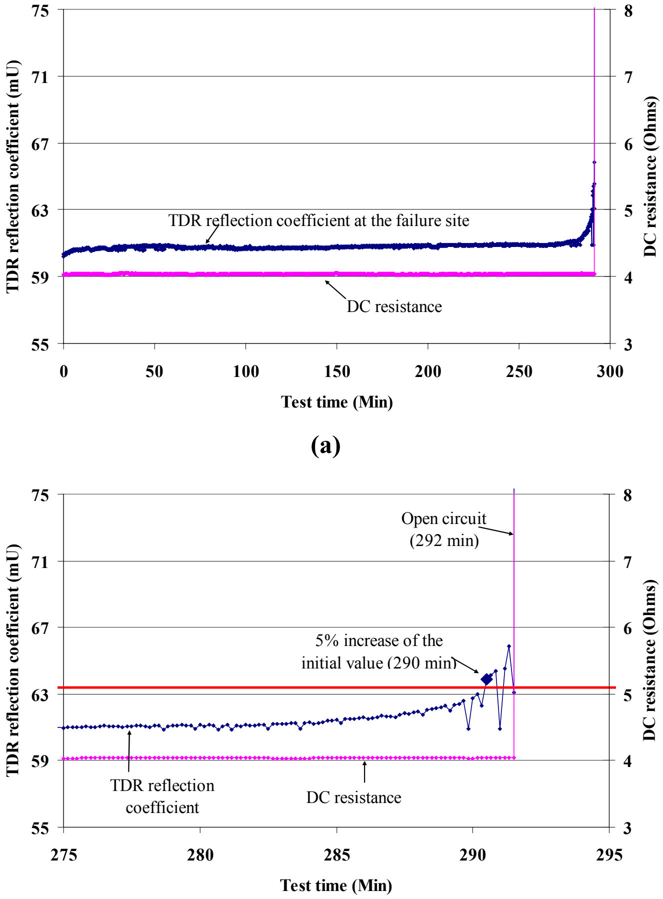


Figure 6 – The TDR response before and after the experiment

The physical locations corresponding to the peaks were identified experimentally through association with known features in the circuit. The change in amplitude of the middle peak was a response from the failure site, which was visually confirmed to be a cracked solder joint.

Figure 7 shows the results of one such shear test experiment, comparing the TDR reflection coefficient at the failure site with the DC resistance. The total duration of this test was about 292 minutes. Both the TDR reflection coefficient and the DC resistance were collected every 10 seconds until the shear stress resulted in a DC open circuit. At the beginning of the test, both measurements remained close to their initial values. The TDR reflection coefficient began to increase about 10 minutes prior to the separation of the solder joint, while DC resistance remained almost constant until it exhibited a sudden increase, indicating a DC open circuit. Increases of the initial TDR reflection coefficient by 5% and 10% were recorded 2 minutes and 10 seconds prior to the failure, respectively. From a series of similar experiments, it was found that these test results were qualitatively repeatable though their initial values were slightly different depending on the applied force and the amount of solder. Figure 8 shows a similar comparison between the TDR reflection coefficient and the DC resistance during another shear test.



(a)

(b)

Figure 7 – Comparison between RF and DC responses during the shear test, (a) over the entire test duration and (b) at the end of the test

After the shear test, one solder joint was still making electrical contact in spite of the partial crack; however, the other joint was completely separated from the circuit trace. It was observed that the RF signal transmitted first across cracked solder joint was reflected back at somewhere between the cracked and the separated solder joint, not at the separated solder joint. In other words, most of the RF signal was attenuated after it passed the cracked solder joint. This phenomenon was also observed from the frequency domain analysis of the cracked solder joint. In order to conduct the frequency domain analysis, a gate, which provides an ability to selectively include the RF response of the region of interest, was applied in the time domain around the cracked solder joint. Figure 9 shows the analysis result, which exhibited a gradual increase of impedance with increasing frequency. The impedance drop at the upper end of the gated frequency response was observed due to the sharp truncation of the gate, as explained in [7]. This clearly shows that higher frequency signals are more sensitive to the impedance changes that accompany physical degradation of the solder joint.

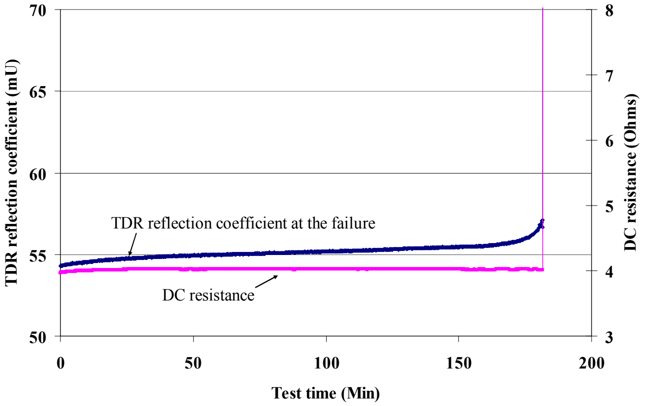


Figure 8 – Comparison between RF and DC responses from a second shear test

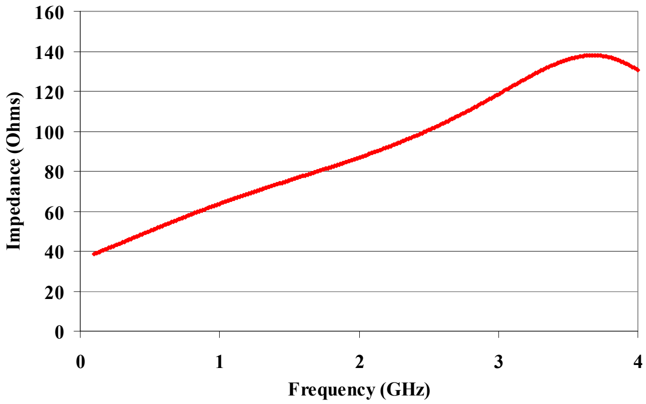


Figure 9 – Frequency domain analysis of the cracked solder joint

This set of experiments thus showed that the combination of an impedance controlled board with an SMT low pass filter and two bias tees was an appropriate test vehicle for monitoring RF and DC responses simultaneously. Also, TDR reflection coefficient was a useful parameter for monitoring circuit impedance changes to detect interconnect degradation. The test results showed that the TDR reflection coefficient exhibited earlier sensitivity than the DC resistance in response to solder joint degradation, and these results were qualitatively repeatable over multiple trials. Therefore, RF impedance analysis can serve as a non-destructive early indicator of solder joint degradation.

Conclusions

A technique for detecting solder joint degradation using RF impedance has been presented in this study. A test vehicle was developed to allow direct comparison of RF and DC measurements to monitor solder joint degradation. The test results confirmed and demonstrated that RF impedance exhibits earlier sensitivity to solder joint degradation than does DC resistance.

These results imply that reliability assessment based on DC resistance measurements may overestimate the lifetime of high speed electronic assemblies. Reliability data on printed circuit board assemblies are often obtained by monitoring resistance of daisy-chained components using dataloggers or event detectors. For products whose performance is dependent on transmission of signals with frequency content of several hundred MHz or more, these methods may overestimate the times-to-failure and thus predict longer lifetimes than would be experienced during product use. RF impedance can provide a more accurate assessment of the reliability of high speed electronic products in response to solder joint cracking. Impedance measurements are likely to provide similar benefits when used to detect other interconnect failure mechanisms, such as corrosion, which are also initiated at external surfaces.

In addition to serving as a tool for laboratory assessment of reliability, RF impedance can serve as a real-time monitor of system performance based on changes in signal integrity. Early detection of interconnect degradation extends the time available for condition-based maintenance, which increases availability of the electronic products. This technique shows potential as a prognostic tool that can provide advanced warning of impending interconnect failures. By incorporation into sensing circuitry that is either located on board in an assembly or in external diagnostic hardware, it can improve real-time reliability prediction of electronic products.

Finally, RF impedance offers advantages as a research tool for studying solder joint failure mechanisms at intermediate stages of progress prior to complete failure. Studies currently underway indicate that solder joint reliability tests which are halted upon observing specified increases in impedance provide an opportunity to perform detailed studies of crack propagation prior to complete separation. Studies such as this can lead to insights into the damage accumulation process.

Future work on this topic will involve investigation of alternative mechanical and thermal loading conditions, improved control and measurement of load and displacement, testing of more complex test vehicles and interconnect structures, and failure analysis prior to solder joint separation.

Acknowledgments

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