Early Detection of Interconnect Degradation by Continuous Monitoring of RF Impedance

Daeil Kwon, Member, IEEE, Michael H. Azarian, Member, IEEE, and Michael Pecht, Fellow, IEEE

Abstract—Traditional methods used to monitor interconnect reliability are based on measurement of dc resistance. DC resistance is well suited for characterizing electrical continuity, such as identifying an open circuit, but is not useful for detecting a partially degraded interconnect. Degradation of interconnects, such as cracking of solder joints due to fatigue or shock loading, usually initiates at an exterior surface and propagates toward the interior. At frequencies above several hundred megahertz, signal propagation is concentrated at the surface of interconnects, a phenomenon known as the skin effect. Due to the skin effect, RF-impedance monitoring offers a more sensitive and reproducible means of sensing interconnect degradation than dc resistance. Since the operation of many types of electronic product requires transmission of signals with significant frequency components in the gigahertz range, this has the further implication that even a small crack at the surface of an interconnect may adversely affect the performance of current and future electronics. This paper demonstrates the value of RF-impedance measurements as an early indicator of physical degradation of solder joints as compared to dc-resistance measurements. Mechanical-fatigue tests 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 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 the early stages of cracking of the solder joint while the dc resistance remained constant. Failure analysis revealed that the RF-impedance increase resulted from a physical crack, which initiated at the surface of the solder joint and propagated only partway across the solder joint. A comparison between RF-impedance and event detectors was made to compare their respective sensitivities in detecting interconnect degradation. These test results indicate that RF impedance can serve as a nondestructive early indicator of solder-joint degradation and as an improved means for assessing reliability of high-speed electronics.

Index Terms—Impedance, interconnection, reliability, time-domain analysis.

I. 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 board-level interconnects include solder joints, printed-circuit-board traces, component leads, and connectors. These interconnects are susceptible to failure by mechanisms such as fatigue [1]–[4], creep [5], corrosion [6], and mechanical overstress [7], [9], which are generally caused by cracks or chemical reactions that initiate in the circumferential area and propagate inward. Fig. 1 shows a summary of the typical loading conditions leading to interconnect failure and the corresponding failure mechanisms.

For reliability monitoring of electronic products, the electronics industry has been using either event detectors or data loggers, which monitor dc resistance [8]–[10]. Typically, dc resistance responds to a short or an open state of a conductor quite well; however, it is not well suited to indicate transitional states such as a partially degraded interconnect. Several researchers have endeavored to detect the degradation of an interconnect using dc resistance [10]–[12]. Qi et al. [10] showed that the measurement technique influenced the detection of failure of solder joints and pointed out some limitations of detection methods using dc resistance. Constable and Lizzul [11] investigated the resistance changes of lap-shear solder joints using resistance spectroscopy, which requires complex experimental and analysis techniques. Caers et al. [12] observed an increase of the solder-joint resistance in the range of 600 mΩ as a crack propagated, which was too small to be detected by 70 typical resistance-monitoring techniques. Since these resistance changes during interconnect degradation are so small, dc resistance is neither sensitive to the early stages of interconnect degradation, such as a partial crack of a solder joint, nor does it provide a sensitive and practical means of monitoring degradation. Incipient degradation may adversely affect the performance of high-speed electronic products. Thus, when dc resistance is used to assess interconnect reliability, it may overestimate lifetime and preclude the opportunity to conduct preventive maintenance, allowing the probability of severe damage to the system. The successful detection of incipient degradation can provide a valuable basis for early prediction of the remaining useful life of electronic systems. Therefore, a new technique is required to overcome the shortcomings of dc resistance as a reliability-monitoring tool.

At frequencies of several hundred megahertz or more, signal propagation of electronic assemblies is more sensitive to mechanical degradation of interconnects than it is at lower frequencies due to surface concentration of the signal. At high operating frequencies, signal propagation is concentrated at the surface of interconnects. This phenomenon is known as the skin effect. “Skin depth” refers to the thickness of the conductor.
within which approximately 63% of the current is contained [13]. Fig. 2 shows current-density distribution in a conductor as a function of multiples of skin depth. As shown as follows, the skin depth $\delta$ is directly related to the frequency $f$ and the resistivity of the conductor $\rho$:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

where $\mu$ denotes the material’s permeability.

Due to the skin effect, RF impedance shows an increase in response to physical degradation at the surface earlier than dc resistance. 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, is capable of detecting small cracks. Fig. 3 shows a conceptual representation of the increased sensitivity of RF-impedance measurements to the physical degradation of interconnects.

Fig. 1. Typical causes of interconnect failure.

Fig. 2. Current density versus multiples of skin depth.

Fig. 3. Conceptual representation of increased sensitivity of RF impedance to interconnect degradation; $t_f$ is the time to complete separation of the interconnect (open circuit), and $\Delta t_{RF}$ and $\Delta t_{DC}$ are the advanced warnings of failure provided by RF impedance and dc resistance, respectively.

detection in a transmission line by monitoring changes in the leakage-conductance parameter calculated from S-parameter measurements. Jong and Tripathi [17] used time-domain reflectometry (TDR) to characterize typical interconnect discontinuities in a high-speed circuit. Most studies were focused on detection of defects or voids in a signal transmission line. However, Kwon et al. [18] reported the first study that demonstrated the increased sensitivity of RF impedance as compared to dc resistance in detecting interconnect degradation during in situ monitoring of both responses.

In order to quantify the increased sensitivity of RF impedance and to investigate the process of physical degradation of an interconnect, stress conditions were controlled using a load unit in this paper. A simple test vehicle that contained two solder joints was employed. The simultaneous measurement of RF impedance and dc resistance allowed direct comparison of their respective sensitivities in detecting the physical degradation of solder joints and to quantify the differences in time-to-failure. Failure analysis of degraded solder joints was conducted to characterize the extent of physical degradation associated with the observed changes of both RF impedance and dc resistance at intermediate stages of solder-joint degradation. Finally, an event detector was incorporated into the test circuit to compare the sensitivity to the early stage detection.
of interconnect degradation of RF impedance with a method widely regarded as the best means of detecting solder-joint failure under cyclic-loading conditions.

II. METHODOLOGY

A. RF Impedance and the Skin Effect

Impedance is a measure of the overall opposition of an electrical circuit to an alternating current at a given frequency [19]. It has three components: resistive, inductive reactance, and capacitive reactance. Resistance depends on the physical properties and dimensions of conductor such as the resistivity, the length of the material, and the cross-sectional area. Signal frequency affects resistance because, at high frequency, the effective cross-sectional area of a conductor is reduced due to the skin effect, which is referred to as ac resistance. Reactance also depends on the signal frequency. Inductive reactance is roughly proportional to the 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.

In order for RF impedance to exhibit enhanced sensitivity to interconnect degradation, the skin depth should be much less than the interconnect thickness. Fig. 4 shows the relationship between the frequency and the skin depth for copper and eutectic tin–lead solder as compared to the typical dimensions of these two kinds of interconnects. As shown in Fig. 4, the skin depth for both copper and eutectic tin–lead becomes less than about a tenth of the interconnect thickness above approximately 500 MHz. Since many commercial products are currently operating in the frequency range of a few gigahertz, in this paper, the monitored frequency window is chosen to be 500 MHz–6 GHz. For eutectic tin–lead solder, the skin depths corresponding to the lower and upper frequencies are 8.5 and 2.5 μm, respectively.

B. S-Parameters and TDR

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 measuring reflection ($S_{11}$) and transmission ($S_{21}, S_{12}$) coefficients over either the frequency or the time domain. A frequency-domain measurement shows the effect of impedance 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 impedance discontinuities as discrete peaks with respect to their positions in the circuit. This is useful in identifying fault locations.

While a typical time-domain measurement uses a sine wave to characterize the circuit, a time-domain measurement using a network analyzer is a little more complicated. The network analyzer sweeps across the frequency range defined by the user and collects the S-parameters according to the frequencies. The network analyzer then applies an inverse fast Fourier transform to the frequency-domain results and obtains the time-domain measurement results. Therefore, the time-domain measurement using a network analyzer is a composite response over all the frequencies monitored. Fig. 5 shows a comparison between frequency- and time-domain analysis. Since this paper 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-propagation speed, which is close to the speed of light, depends on the medium where the signal travels. The signal speed can be calculated from the signal-transit time over a feature of known length, such as a wire. Therefore, the distance from a reference point (the end point where calibration has been conducted) to the location of an unknown impedance discontinuity may be calculated by multiplying the speed of the electrical signal by half the measured signal-transit time. In this paper, 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 TDR reflection coefficient, which is essentially a ratio of the reflected voltage of the signal sent 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 solder-joint location. As shown in (2), the TDR reflection coefficient ($\Gamma$) can range from −1 to 1, which correspond to the impedance values of zero and infinity, respectively. It may be conveniently reported in milliunits (mU)

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

where $Z_L$ and $Z_0$ denote the impedance of device under test and characteristic impedance of the circuit, respectively.

TDR has been found to be an effective method for evaluating impedance discontinuities in transmission lines [17], [20], [29] BGAs [21], [22], QFPs [23], and flip chips [24]. TDR also identifies fault locations. This is useful in identifying fault locations.

Fig. 4. Comparison between skin depth and interconnect dimensions.
be used to diagnose changes in such small structures. In this paper, we demonstrate how TDR can be implemented as a prognostic tool that provides an early indication of failure when it is incorporated into an \textit{in situ} monitoring circuit. The following section describes the experimental procedures used to demonstrate the ability of TDR to detect early stages of interconnect degradation and compares that capability with that of dc-resistance measurements made using either a digital multimeter or an event detector.

### III. Experiment

#### A. Apparatus

A test circuit for simultaneous measurement of the RF impedance and the dc resistance was developed and is shown in Fig. 6. The test circuit consisted of the following: an impedance-controlled circuit board with a surface-mount technology (SMT) low-pass filter, two bias tees, RF cables, and measurement instruments. The circuit board had a controlled characteristic impedance of 50 $\Omega$ to match that of the test equipment, cables, and other components. An SMT low-pass filter was soldered to this circuit board using eutectic tin–lead solder. The cutoff frequency of the low-pass filter was 6.7 GHz. Since the frequency range used in this paper was between 500 MHz and 6 GHz, the filter acted as a conductor with the same characteristic impedance of 50 $\Omega$.

In order to allow simultaneous monitoring of the RF impedance and the dc resistance, bias tees were incorporated into the test circuit. The bias tees extracted or combined the RF and dc signals in order to allow for simultaneous monitoring of RF impedance and dc resistance. The dc and the RF measurement instruments were connected to the dc and 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 $\Omega$.

A Keithley 2010 7.5-digit multimeter and an Agilent E8364A vector network analyzer (VNA) were used to monitor the dc and RF impedance, respectively. The VNA had a frequency range of 45 MHz–50 GHz and was configured with TDR functionality. Both instruments were externally monitored to allow automated data acquisition. For some tests, an AnalysisTech STD128 event detector was substituted for the digital multimeter to compare RF impedance to the type of high-speed monitoring equipment, which is widely used by the electronics industry.
An MTS Tytron 250 was used to apply a cyclic shear force to the solder joint in order to generate fatigue failures. The MTS Tytron 250 is a uniaxial microtester that has a load capacity of 250 N and a load resolution of 0.001 N. According to the user’s needs, various load profiles can be programmed, e.g., a cyclic shear force to generate fatigue failure or a monotonically increasing force to measure the strength of a material. The programmed force can be monitored along with the displacement, which provides the force and displacement profiles during stress testing. A strip of alumina was inserted between the metal tip of the force transducer and the component to avoid electrical connection at the contact.

### B. Validation of Electrical Measurements During Stress Testing

RF impedance is sensitive to electromagnetic interference generated by electronic equipment around the device under test. In addition, the application of a mechanical load may affect the RF-impedance measurements due to the physical contact with the component. Therefore, in order to evaluate the effect of any electromagnetic interference on the RF-impedance and dc-resistance measurements, the RF impedance and dc resistance were measured under three test conditions, as shown in Table I.

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tytron 250 status</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Application of load</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The three test conditions were the combinations of the operational status of the Tytron 250 and the application of load to the component. Three measurements for each condition were taken to ensure repeatability of the test results. It was observed that the measurement variations among the three conditions were less than 1%, which verified that the operation of the Tytron 250 did not introduce any measurable electrical noise into the RF impedance or dc resistance.

### C. Load-Profile Design

In order to determine an appropriate force level for the fatigue tests, the shear strength of the solder joint was measured using the same test vehicles described earlier. A monotonically increasing shear force was applied to the component at a displacement rate of 0.5 mm/s until the solder joints were separated. In this experiment, however, the failure mode was copper-pad separation from the circuit board, rather than cracking of the solder joints. In order to avoid copper-pad separation during the shear-strength measurement, the SMT component was soldered to the ground plane of the same circuit board, and the measurements were repeated. The solder-joint shear strength was identified to be about 125 N, averaged over multiple trials.

### D. TDR Reflection-Coefficient Measurement

The TDR reflection coefficients at particular locations of interest were extracted from the overall time-domain plot. Fig. 8 shows two measurements of the TDR reflection coefficient over the signal-transit time domain: One taken prior to the application of the cyclic stress and the other after completion of a fatigue test. The physical locations corresponding to the peaks were identified experimentally through association with known features in the circuit. The change in amplitude of the peak was a result of an increase in impedance at the failure site, which was visually confirmed to be a cracked solder joint.

### E. RF and DC Data Acquisition

Both the RF and the dc responses were collected every 30 s. Instrumental control software was used to instruct the multimeter to collect the dc resistance and the TDR reflection.
coefficients over the entire time domain periodically. One set of TDR measurement data contained a collection of reflection-coefficient values over the signal path of the circuit board. In order to compare to the dc-resistance measurements, the TDR reflection coefficients at the failure site were extracted and displayed in one plot as a function of test duration. Each experiment was conducted until it resulted in a dc open circuit or until the TDR reflection coefficient increased significantly.

IV. RESULTS

A. Comparison Between RF Impedance and DC Resistance

Fig. 9 shows the results of one fatigue test, which compares the TDR reflection coefficient at the failure site with the dc resistance. The total duration of this test was 1303 min. Both the TDR reflection coefficient and the dc resistance were collected and displayed in one plot as a function of test duration. Each experiment was conducted until it resulted in a dc open circuit or until the TDR reflection coefficient increased significantly.

B. Failure Analysis of Degraded Solder Joint

Fig. 10 shows the result of another fatigue test comparing the TDR reflection coefficient at the failure site with the dc resistance. As observed in the previous result, both dc and RF responses remained around their initial values at the beginning of the test, but the TDR reflection coefficient began to increase as the solder joints were stressed. In order to investigate the physical degradation of the solder joint, which was responsible for the RF-impedance changes, the test was stopped after 308 min of operation when the TDR reflection coefficient showed a 4-mU increase from its initial value. This partially degraded solder-joint sample was used to relate the failure mechanism and the extent of damage to the RF-impedance changes.

After the test, the circuit board was initially inspected under the scanning electron microscope (SEM) to locate any damage to the solder joints. The SEM revealed an externally visible crack in the solder joint along the interface between the component and the copper pad on the circuit board. The sample was potted in epoxy and cross sectioned to reveal the cracked solder joint on a plane orthogonal to the long axis of the filter, as shown in Fig. 11.

Fig. 12 shows several cross-sectional SEM images of the degraded solder joint. A crack, which initiated at the surface and propagated inward, may be clearly observed, as shown in Fig. 12(a). The crack has opened on the side of the solder joint, where the shear force was applied and propagated toward the center, consistent with the direction of the applied shear force, as shown at higher magnification in Fig. 12(b). On the other 403
hand, the opposite side of the solder joint was still intact, as shown in Fig. 12(c), with the possible exception of a microcrack near the outside corner of the copper pad.

Analysis of the figures revealed that the total crack length was about 700 µm, which is much greater than the skin depth near the outside corner of the copper pad.

Fig. 12. Cross-sectional SEM image of component and solder joint. (a) Overview. (b) Left-hand side close-up. (c) Right-hand side close-up.

C. Comparison With Event Detectors

In order to continuously monitor the dc resistance of the solder joints, an event detector was incorporated into the test circuit in place of the digital multimeter and configured to have a threshold resistance of 1000 Ω according to the IPC-SM-785 standard [8]. Event detectors are one of the commercially available instruments commonly used by the electronics industry to monitor the reliability of electronic products [8]. The effect of the high-frequency signals and the RF components on the event-detector measurement was evaluated to determine whether the event detector might be affected by the signals of a few gigahertz or the bias tees. By introducing an electrical discontinuity into the test circuit, it was confirmed that the operation of the event detector was not influenced by the high-frequency signals and components which had been used in the fatigue tests shown in the previous section.

In a fatigue test, the event-detector results were polled out once per second and displayed in a plot together with the TDR reflection coefficient at the failure site. The output value from the event detector was either zero or one, which indicated a short or an open circuit, respectively. Fig. 13 shows the result from a fatigue test conducted with an event detector. The first occurrence that exceeded the initial TDR reflection coefficient by 5% was observed at 1619 min, while the event detector did not catch any transitional dc open states until 2134 min at which time the test was stopped and the solder-joint separation was observed.

This test result shows that, even at the relatively low monitoring frequency of once every 30 s, RF impedance detects interconnect degradation earlier than dc resistance. It also demonstrates that RF impedance can serve as a better reliability-monitoring tool than an event detector. In spite of the continuous high-speed sampling of the event detector, it failed to provide early warning prior to RF impedance nor even before solder-joint separation. Although the time to TDR reflection-coefficient increase and time to failure varied from sample to sample, the results were qualitatively repeatable, although the actual values of the initial TDR reflection coefficient and the dc resistance were slightly different, depending on the size and shape of the solder fillet.
RF-impedance monitoring can be used not only for diagnostic purposes but also as a prognostic tool. In situ measurements can be compared to an appropriate threshold that allows for the identification of the time at which the interconnect starts to degrade. This event can be a failure precursor, which can trigger an alarm to provide condition-based maintenance, thereby reducing product availability, reducing unplanned downtime, and potentially bringing substantial savings in operational, repair, logistical, and liability costs. This technique can also improve real-time reliability prediction of electronic products when incorporated into sensing circuitry that is either located or on a circuit board in an assembly or in external diagnostic hardware.

Future work on this topic will involve an investigation of alternative mechanical- and thermal-loading conditions, further quantification of the relationship between crack length and RF impedance, improved control and measurement of load and displacement, and testing of more complex test vehicles and interconnect structures.

REFERENCES


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**AQ2**


**AQ3**


AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

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AQ2 = The author’s current affiliation indicated in the footnote did not correspond to the current affiliation provided in the curriculum vitae. Please check.
AQ3 = Current affiliation was provided in the vitae. Please check if appropriate.
AQ4 = The “Bachelors” and “Masters” degrees were captured as “B.S.” and “M.S.” degrees, respectively. Please check if OK.
AQ5 = The author’s current affiliation indicated in the footnote did not correspond to the current affiliation provided in the curriculum vitae. Please check.
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END OF ALL QUERIES
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I. INTRODUCTION

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High-frequency signal parameters, such as scattering parameters (or S-parameters), RF impedance, and time-domain reflection coefficient, have previously been used to characterize a degraded interconnect [14]-[18]. For example, Putaala et al. [14] performed temperature-cycling testing on BGA components under ex situ monitoring of the signal return loss ($S_{11}$), one of the S-parameters, and dc resistance. Ghaffarian et al. [15] also conducted temperature-cycling testing on BGA packages to characterize RF interconnects using S-parameters. Foley et al. [16] presented an approach for void detection in a transmission line by monitoring changes in the leakage-conductance parameter calculated from S-parameter measurements. Jong and Tripathi [17] used time-domain reflectometry (TDR) to characterize typical interconnect discontinuities in a high-speed circuit. Most studies were focused on detection of defects or voids in a signal transmission line. However, Kwon et al. [18] reported the first study that demonstrated the increased sensitivity of RF impedance as compared to dc resistance in detecting interconnect degradation during in situ monitoring of both responses.

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\[ \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \]  

where \( Z_L \) and \( Z_0 \) denote the impedance of device under test and characteristic impedance of the circuit, respectively.

TDR has been found to be an effective method for evaluating impedance discontinuities in transmission lines [17], [20], [22], [24], [26], and characteristic impedance of the circuit, respectively. TDR also offers the ability to detect degradation and isolate it at the specific level of individual solder joints in a daisy chain. For example, during system operation, solder joints in each location may experience different loading conditions, which could result in different levels of degradation. TDR reflection coefficient can be used to characterize electrical performance. S-parameters can be measured by using a network analyzer to send high-speed signals through the circuit and measuring reflection (\( S_{11} \)) and transmission (\( S_{21}, S_{22} \)) coefficients over either the frequency or the time domain. A frequency-domain measurement shows the effect of impedance 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 impedance discontinuities as discrete peaks with respect to their positions in the circuit. This is useful in identifying fault locations.

While a typical time-domain measurement uses a sine wave to characterize the circuit, a time-domain measurement using a network analyzer is a little more complicated. The network analyzer sweeps across the frequency range defined by the user and collects the S-parameters according to the frequencies. The network analyzer then applies an inverse fast Fourier transform to the frequency-domain results and obtains the time-domain measurement results. Therefore, the time-domain measurement using a network analyzer is a composite response over all the frequencies monitored. Fig. 5 shows a comparison between frequency- and time-domain analysis. Since this paper focuses on the solder-joint degradation that occurs at specified locations in the circuit, a time-domain analysis was conducted.

In order for RF impedance to exhibit enhanced sensitivity to interconnect degradation, the skin depth should be much less than the interconnect thickness. Fig. 4 shows the relationship between the frequency and the skin depth for copper and eutectic tin–lead solder as compared to the typical dimensions of these two kinds of interconnects. As shown in Fig. 4, the skin depth for both copper and eutectic tin–lead becomes less than about a tenth of the interconnect thickness above approximately 500 MHz. Since many commercial products are currently operating in the frequency range of a few gigahertz, the monitored frequency window is chosen to be in the range of 500 MHz–6 GHz. For eutectic tin–lead solder, the skin depths for both copper and eutectic tin–lead becomes less than about a tenth of the interconnect thickness above approximately 500 MHz–6 GHz. For eutectic tin–lead solder, the skin depths corresponding to the lower and upper frequencies are 8.5 and 2.5 µm, respectively.

B. S-Parameters and TDR

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 measuring reflection (\( S_{11} \)) and transmission (\( S_{21}, S_{22} \)) coefficients over either the frequency or the time domain. A frequency-domain measurement
be used to diagnose changes in such small structures. In this paper, we demonstrate how TDR can be implemented as a prognostic tool that provides an early indication of failure when it is incorporated into an in situ monitoring circuit. The following section describes the experimental procedures used to demonstrate the ability of TDR to detect early stages of interconnect degradation and compares that capability with that of dc-resistance measurements made using either a digital multimeter or an event detector.

III. EXPERIMENT

A. Apparatus

A test circuit for simultaneous measurement of the RF impedance and the dc resistance was developed and is shown in Fig. 6. The test circuit consisted of the following: an impedance-controlled circuit board with a surface-mount technology (SMT) low-pass filter, two bias tees, RF cables, and measurement instruments. The circuit board had a controlled characteristic impedance of 50 Ω to match that of the test equipment, cables, and other components. An SMT low-pass filter was soldered to this circuit board using eutectic tin–lead solder. The cutoff frequency of the low-pass filter was 6.7 GHz. Since the frequency range used in this paper was between 500 MHz and 6 GHz, the filter acted as a conductor with the same characteristic impedance of 50 Ω.

In order to allow simultaneous monitoring of the RF impedance and the dc resistance, bias tees were incorporated into the test circuit. The bias tees extracted or combined the RF and dc signals in order to allow for simultaneous monitoring of RF impedance and dc resistance. The dc and the RF measurement instruments were connected to the dc and 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 Ω.

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–50 GHz and was configured with TDR functionality. Both instruments were externally monitored to allow automated data acquisition. For some tests, an AnalysisTech STD128 event detector was substituted for the digital multimeter to compare RF impedance to the type of high-speed monitoring equipment, which is widely used by the electronics industry.
TABLE I
Test Matrix to Evaluate the Effect of Tytron 250 Operation

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tytron 250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>status</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Application of</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>load</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An MTS Tytron 250 was used to apply a cyclic shear force to the solder joint in order to generate fatigue failures. The MTS Tytron 250 is a uniaxial microtester that has a load capacity of 250 N and a load resolution of 0.001 N. According to the user’s needs, various load profiles can be programmed, e.g., a cyclic shear force to generate fatigue failure or a monotonically increasing force to measure the strength of a material. The programmed force can be monitored along with the displacement, which provides the force and displacement profiles during stress testing. A strip of alumina was inserted between the metal tip of the force transducer and the component to avoid electrical connection at the contact.

B. Validation of Electrical Measurements During Stress Testing

RF impedance is sensitive to electromagnetic interference generated by electronic equipment around the device under test. In addition, the application of a mechanical load may affect the RF-impedance measurements due to the physical contact with the component. Therefore, in order to evaluate the effect of any electromagnetic interference on the RF-impedance and dc-resistance measurements, the RF impedance and dc resistance were measured under three test conditions, as shown in Table I. The three test conditions were the combinations of the operational status of the Tytron 250 and the application of load to the component. Three measurements for each condition were taken to ensure repeatability of the test results. It was observed that the measurement variations among the three conditions were less than 1%, which verified that the operation of the Tytron 250 did not introduce any measurable electrical noise into the RF impedance or dc resistance.

C. Load-Profile Design

In order to determine an appropriate force level for the fatigue tests, the shear strength of the solder joint was measured using the same test vehicles described earlier. A monotonically increasing shear force was applied to the component at a displacement rate of 0.5 mm/s until the solder joints were separated. In this experiment, however, the failure mode was copper-pad separation from the circuit board, rather than cracking of the solder joints. In order to avoid copper-pad separation during the shear-strength measurement, the SMT component was soldered to the ground plane of the same circuit board, and the measurements were repeated. The solder-joint shear strength was identified to be about 125 N, averaged over multiple trials.

D. TDR Reflection-Coefficient Measurement

The TDR reflection coefficients at particular locations of interest were extracted from the overall time-domain plot. Fig. 8 shows two measurements of the TDR reflection coefficient over the signal-transit time domain: One taken prior to the application of the cyclic stress and the other after completion of a fatigue test. The physical locations corresponding to the TDR peaks were identified experimentally through association with known features in the circuit. The change in amplitude of the TDR peak was a result of an increase in impedance at the failure site, which was visually confirmed to be a cracked solder joint.

E. RF and DC Data Acquisition

Both the RF and the dc responses were collected every 30 s. Instrumental control software was used to instruct the multimeter to collect the dc resistance and the TDR reflection coefficient.
coefficients over the entire time domain periodically. One set of TDR measurement data contained a collection of reflection-coefficient values over the signal path of the circuit board. In order to compare to the dc-resistance measurements, the TDR reflection coefficients at the failure site were extracted and displayed in one plot as a function of test duration. Each experiment was conducted until it resulted in a dc open circuit or until the TDR reflection coefficient increased significantly.

IV. RESULTS

A. Comparison Between RF Impedance and DC Resistance

Fig. 9 shows the results of one fatigue test, which compares the TDR reflection coefficient at the failure site with the dc resistance. The total duration of this test was 1303 min. Both the TDR reflection coefficient and the dc resistance were collected every 30 s until the applied stress resulted in a dc open circuit. As shown in Fig. 9(a), at the beginning of the test, both measurements remained close to their initial values. The TDR reflection coefficient began to increase about 36 min prior to the separation of the solder joint, while the dc resistance remained almost constant until it exhibited a sudden increase, indicating a dc open circuit. Fig. 9(b) shows that the first occurrences that exceeded the initial TDR reflection coefficient by 5%, 10%, and 15% were recorded 36.5, 3.5, and 1 min prior to the failure, respectively. In order to relate these increases of the TDR reflection coefficient to the physical degradation of the solder joint, a failure analysis was conducted on a partially degraded solder-joint sample generated during another similar test.

B. Failure Analysis of Degraded Solder Joint

Fig. 10 shows the result of another fatigue test comparing the TDR reflection coefficient at the failure site with the dc resistance. As observed in the previous result, both dc and RF responses remained around their initial values at the beginning of the test, but the TDR reflection coefficient began to increase as the solder joints were stressed. In order to investigate the physical degradation of the solder joint, which was responsible for the RF-impedance changes, the test was stopped after 308 min of operation when the TDR reflection coefficient showed about 3.8 mU increase from its initial value. This partially degraded solder-joint sample was used to relate the failure mechanism and the extent of damage to the RF-impedance changes.

After the test, the circuit board was initially inspected under the scanning electron microscope (SEM) to locate any damage to the solder joints. The SEM revealed an externally visible crack in the solder joint along the interface between the component and the copper pad on the circuit board. The sample was potted in epoxy and cross sectioned to reveal the cracked solder joint on a plane orthogonal to the long axis of the filter, as shown in Fig. 11.

Fig. 12 shows several cross-sectional SEM images of the degraded solder joint. A crack, which initiated at the surface and propagated inward, may be clearly observed, as shown in Fig. 12(a). The crack has opened on the side of the solder joint where the shear force was applied and propagated toward the center, consistent with the direction of the applied shear force, as shown at higher magnification in Fig. 12(b). On the other
hand, the opposite side of the solder joint was still intact, as shown in Fig. 12(c), with the possible exception of a microcrack near the outside corner of the copper pad. Analysis of the figures revealed that the total crack length was about 700 µm, which is much greater than the skin depth under the given conditions. By this time in the fatigue test, the TDR reflection coefficient had increased by 4 mU, about 3% of the initial TDR reflection coefficient, but the dc resistance remained at its initial value. This provides clear evidence that RF impedance is more sensitive than dc resistance in detecting interconnect degradation due to the skin effect. Other experiments confirmed that these test results were qualitatively repeatable, although the actual values of the initial TDR reflection coefficient and the dc resistance were slightly different, depending on the size and shape of the solder fillet.

C. Comparison With Event Detectors

In order to continuously monitor the dc resistance of the solder joints, an event detector was incorporated into the test circuit in place of the digital multimeter and configured to have a threshold resistance of 1000 Ω according to the IPC-SM-785 standard [8]. Event detectors are one of the commercially available instruments commonly used by the electronics industry to monitor the reliability of electronic products [8]. The effect of the high-frequency signals and the RF components on the event-detector measurement was evaluated to determine whether the event detector might be affected by the signals of a few gigahertz or the bias tees. By introducing an electrical discontinuity into the test circuit, it was confirmed that the operation of the event detector was not influenced by the high-frequency signals and components which had been used in the fatigue tests shown in the previous section.

In a fatigue test, the event-detector results were polled out once per second and displayed in a plot together with the TDR reflection coefficient at the failure site. The output value from the event detector was either zero or one, which indicated a short or an open circuit, respectively. Fig. 13 shows the result from a fatigue test conducted with an event detector. The first occurrence that exceeded the initial TDR reflection coefficient by 5% was observed at 1619 min, while the event detector did not catch any transitional dc open states until 2134 min at which time the test was stopped and the solder-joint separation was observed. This test result shows that, even at the relatively low monitoring frequency of once every 30 s, RF impedance detects interconnect degradation earlier than dc resistance. It also demonstrates that RF impedance can serve as a better reliability-monitoring tool than an event detector. In spite of the continuous high-speed sampling of the event detector, it failed to provide early warning prior to RF impedance nor even before solder-joint separation. Although the time to TDR reflection-coefficient increase and time to failure varied from sample to sample, RF impedance consistently demonstrated better detection capabilities compared to event detectors.
V. Conclusion

A technique for early detection of interconnect degradation using continuous monitoring of RF impedance has been presented in this paper. A test vehicle was developed to allow direct comparison of RF and dc measurements during cyclic loading of a surface-mount component. This paper 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.

In addition, the TDR reflection coefficient was found to be a useful parameter for monitoring circuit-impedance changes in order to diagnose interconnect degradation. Since at high operating frequencies signal propagation is concentrated in the circumferential region of a conductor, a crack that initiates at the surface raises the RF impedance, thus causing an increase in the TDR reflection coefficient. As a result, the TDR reflection coefficient serves as a dependable indicator of interconnect degradation. This paper showed that a 4-mU increase of the TDR reflection coefficient resulted from a crack extending about halfway across the solder joint of a 1206 component, when monitored using the frequency range of 0.5–6 GHz.

The results of this paper imply that reliability assessment based on dc-resistance measurements, using equipment such as event detectors, may overestimate the lifetime of high-speed electronic assemblies. Currently, reliability data on printed-circuit-board assemblies are often obtained by monitoring the dc resistance of daisy-chained components using data loggers or event detectors. For products whose performance is dependent on the transmission of signals with a frequency of several hundred megahertz or more, even a small crack may degrade the high-speed signal integrity, while it would not affect low-speed signals such as dc resistance. Therefore, dc resistance may overestimate the time-to-failure and, thus, predict longer lifetimes than would be experienced during product use. RF impedance provides more sensitive means of monitoring interconnects, which can provide more accurate assessment of the reliability of high-speed electronic products in response to solder-joint cracking.

Moreover, this technique offers advantages as a research tool for studying solder-joint failure mechanisms at intermediate stages of progress prior to complete failure. As shown in the failure analysis of the degraded solder joint, an increase in RF impedance is associated with a physical crack in the solder joint. The continuous monitoring of RF impedance during a stress test provides a direct means of monitoring the health of an interconnect. Therefore, solder-joint reliability tests halted upon observing specified increases in RF impedance provide an opportunity to perform detailed studies of defect generation and crack propagation prior to complete separation of the solder joint. Statistical techniques for anomaly detection can be paired with RF impedance to determine the earliest increase in RF impedance associated with the cracking of the solder joint. Studies such as this can lead to insights into the damage-accumulation process under a variety of loading conditions.

RF-impedance monitoring can be used not only for diagnostic purposes but also as a prognostic tool. In situ measurements can be compared to an appropriate threshold that allows for the identification of the time at which the interconnect starts to degrade. This event can be a failure precursor, which can trigger an alarm to provide condition-based maintenance, thereby reducing product availability, reducing unplanned downtime, and potentially bringing substantial savings in operational, repair, logistical, and liability costs. This technique can also improve real-time reliability prediction of electronic products when incorporated into sensing circuitry that is either located on a circuit board in an assembly or in external diagnostic hardware.

Future work on this topic will involve an investigation of alternative mechanical- and thermal-loading conditions, further quantification of the relationship between crack length and RF impedance, improved control and measurement of load and displacement, and testing of more complex test vehicles and interconnect structures.

References


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