Detection of Solder Joint Failure Precursors on Tin-Lead and Lead-Free Assemblies using RF Impedance Analysis

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Abstract
During the lifetime of electronic products, interconnects are susceptible to failures by mechanisms such as fatigue, creep, corrosion, and mechanical over-stress. Regardless of the failure mechanisms, interconnect degradation often starts from the surface and propagates inward. DC resistance, which has been used by the electronics industry to monitor the reliability of board level interconnects, does not offer an adequate means to predict an impending failure. However, RF impedance does respond to the early stages of interconnect degradation due to the skin effect, and thus can provide a failure precursor for an interconnect.

In this study, we compared early changes in RF impedance to changes in DC resistance to identify solder joint failure precursors under creep testing conditions. We report the effect of different solder alloys on RF impedance. The test vehicle consisted of an impedance-controlled circuit board, a surface-mount low-pass filter, and two solder joints providing both mechanical and electrical connection between them. The solder alloys under investigation were eutectic tin-lead (Sn-37Pb) and SAC305 (Sn-3.0Ag-0.5Cu). Constant mechanical load was directly applied to the filter at an elevated temperature in order to generate creep failures of the solder joints. During solder joint degradation, RF impedance and DC resistance were simultaneously monitored in order to allow a direct comparison between their respective sensitivities in detecting failure precursors before the solder joint showed a DC open circuit.

The test results showed that regardless of solder alloy RF impedance failure precursors were detectable prior to changes in DC resistance during solder joint degradation. This demonstrates that RF impedance can serve as a non-destructive and real-time degradation indicator of interconnects and can predict impending failures.

Introduction
Electronic products are exposed to various loading conditions during their life cycle, including temperature cycling, vibration, and mechanical over-stress. These loading conditions may result in the failure of interconnects such as solder joints, printed circuit board traces, component leads, and connectors. The failure of interconnects in a product often leads to degradation in performance, improper functioning of the product, and eventually product failure. Traditionally, the electronics industry has used methods based on measurement of DC resistance to monitor the reliability of electronic products under loading conditions. With appropriate sampling techniques, DC resistance can provide an accurate indication of an open circuit, but it is not useful for detecting a partially degraded interconnect.

Degradation of interconnects usually initiates at an exterior surface and propagates towards the interior [1][2]. At frequencies of several hundred MHz or more, signal propagation is more sensitive to the mechanical degradation of interconnects than it is at lower frequencies due to surface concentration of the current, which is known as the skin effect. “Skin depth” refers to the thickness of the conductor within which approximately 63% of the current is contained [3]. As shown in Equation (1), the skin depth, \( \delta \), is directly related to the frequency, \( f \), the resistivity of the conductor, \( \rho \), and the material’s permeability, \( \mu \):

\[
\delta = \sqrt{\frac{\rho \mu}{f \pi}}
\]  

Due to the skin effect, RF impedance shows early changes in response to physical degradation of an interconnect that can serve as failure precursors.

It has been previously reported by the authors [4][5][6] that RF impedance exhibits higher sensitivity than DC resistance to interconnect degradation under cyclic loading and high temperature shear conditions. This study compares changes in RF impedance with changes in DC resistance in order to identify interconnect failure precursors under controlled creep testing conditions. Furthermore, the effect of tin-lead and lead-free assemblies on changes in RF impedance during creep testing is also studied to determine the applicability of RF impedance as a failure precursor to both types of solder alloys.

Interconnect degradation measurement
Time domain reflectometry (TDR) measures impedance discontinuities as discrete peaks with respect to their positions in the circuit, which is useful in identifying fault locations. A TDR measurement is made by launching an impulse or step into the circuit and observing the reflections caused by impedance mismatches with the characteristic impedance of the circuit [7][8]. The outcome of a TDR measurement is often reported as a reflection coefficient (\( \Gamma \)), which can be quantified as the ratio of the reflected voltage of the signal at a port to that of the transmitted signal from the same port. This ratio is expressed as shown in Equation (2):

\[
\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_0}{Z_L + Z_0}
\]
where $Z_L$ and $Z_0$ denote the impedance of the device under test (DUT) and the characteristic impedance of the circuit, respectively.

A time domain measurement using a network analyzer involves measurement over a range of frequencies. The network analyzer sweeps across the frequency range defined by the user and collects the reflection coefficients as a function of the monitored 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. In this study, the TDR reflection coefficient obtained from a network analyzer was used as a measure of RF impedance.

In order to measure DC resistance, a Wheatstone bridge was used in this study, as shown in Figure 1. Bridge circuits are commonly used to measure resistance, capacitance, and inductance [9]. The Wheatstone bridge is a resistive bridge that produces an output in the form of a voltage level that varies as the resistance changes. The Wheatstone bridge provides accurate resistance measurement, which enables the detection of small changes from a nominal value. The four arms of the bridge consist of three equal resistors, $R_1$, $R_2$, and $R_3$, and the DUT, $R_u$. As the resistance of the DUT changes, the output voltage between the nodes B and C, $V_o$, varies. Therefore, the resistance of the DUT can be measured with improved resolution by monitoring the output voltage, $V_o$, during creep testing.

**Experimental setup**

A test circuit was developed to simultaneously monitor the TDR reflection coefficient and the DC resistance during creep testing, as shown in Figure 2. The test circuit included an impedance-controlled circuit board on which a surface mount technology (SMT) low pass filter component was soldered, two bias-tees for extracting and combining the RF and DC signals, a Wheatstone bridge for DC resistance measurement, a vector network analyzer for TDR reflection coefficient measurement, and several RF cables that connected these elements to each other. The components of this circuit were impedance controlled to 50 Ohms in order to match the characteristic impedance of the test equipment.

The test circuit board contained two solder joints that provided both mechanical and electrical connection between the circuit board and the low pass filter component. In order to examine the effect of different solder alloys on changes in RF impedance as the solder joint degraded, this study included both eutectic tin-lead (Sn37Pb) and lead-free SAC305 (Sn3.0Ag0.5Cu) alloy, which are widely used by the electronics industry. All test boards were subjected to creep testing with simultaneous monitoring of the TDR reflection coefficient and the DC resistance.

Using Equation (1), the skin depth for both eutectic tin-lead and SAC305 solder alloys can be calculated as shown in Figure 3. Since many commercial products are currently operating in the frequency range of a few gigahertz, in this study the monitored frequency range was chosen to be 500 MHz to 6 GHz, in which the surface concentration of high speed signals was large enough to expect increased sensitivity of TDR reflection coefficient to physical degradation. The low pass filter had a cut-off frequency of 6.7 GHz, which allowed the signals used to monitor the TDR reflection coefficient to travel through the low pass filter without attenuation. Therefore, the low pass filter acted as a conductor providing two solder joints subjected to creep testing.

![Figure 2: Schematic of the test circuit](image)

**Figure 2: Schematic of the test circuit**

An MTS Tytron 250 was used to apply a constant load to the solder joints and to control the temperature of the chamber in which the test circuit board was placed during creep testing. A Keithley 2010 digital multimeter and an Agilent E8364A vector network analyzer were used to monitor the output voltage of the Wheatstone bridge and the TDR.

![Figure 3: Comparison between skin depth and interconnect dimensions](image)

**Figure 3: Comparison between skin depth and interconnect dimensions**
reflection coefficient, respectively. Both instruments were externally controlled to allow automated data acquisition.

Test conditions

A constant mechanical shear force of 10 N was applied to the component in order to generate creep failures of the solder joints. The test circuit board was put in a temperature chamber where the temperature was held at 125 °C. The homologous temperature was calculated to be 0.87 for eutectic tin-lead, and 0.81 for SAC305, both of which were high enough to expect creep failures. The shear force maintained the contact between the force transducer and the component throughout the entire test until the solder joint was ruptured by creep. A strip of alumina was inserted between the metal tip of the force transducer and the component to avoid electrical connection at the point of contact.

Instrumental control software was used to instruct the multimeter and the vector network analyzer to collect the output voltage of the Wheatstone bridge and the TDR reflection coefficient, respectively, every 30 s. The collected output voltages were converted into the DC resistances using the relationship among the bridge elements. Each set of TDR measurement data contained a set of reflection coefficient values over the partial signal path of the circuit board collected at a particular instant during the creep test. In order to monitor changes to the interconnect over time and allow comparison with DC resistance, the TDR reflection coefficients at the location of a specific solder joint were extracted and displayed in a plot as a function of test duration. During each experiment the TDR responses and the output voltage were simultaneously monitored until the thermo-mechanical stresses resulted in a DC open circuit.

Results

Figure 4 shows the results of a creep test conducted on eutectic tin-lead solder joints. The total duration of the test was 503 minutes. The TDR reflection coefficient and the output voltage of the resistance bridge were collected every 30 s. Both the TDR reflection coefficient and the DC resistance remained close to their initial values at the beginning of the test. However, the TDR reflection coefficient gradually increased as the test progressed, indicating a failure precursor. In spite of the use of the Wheatstone bridge, the DC resistance did not show any changes until it exhibited a sudden increase as a result of a DC open circuit. Figure 5 shows a creep test result conducted on SAC305 solder joints. Since the total duration of a test depended on the initial conditions such as the amount of solder, the responses during the last 500 minutes were provided to show the changes at the end of the test clearly. The gradual increase of the TDR reflection coefficient which was observed towards the end of the test for the SAC305 solder joints was similar to that observed in the tin-lead solder joint case. In general, the same behavior of the TDR reflection coefficient was observed from the creep tests with both solder joints, although the initial conditions varied from sample to sample. Thus, regardless of which solder is used, RF impedance consistently provides interconnect failure precursors under thermo-mechanical loading conditions.

Figure 4: TDR reflection coefficient (in milliunits, mU) and DC resistance during a creep test on a SnPb solder joint

Figure 5: TDR reflection coefficient and DC resistance during a creep test on a SAC305 solder joint

Figure 6 shows another creep test result with eutectic tin-lead solder, comparing the TDR reflection coefficient and the DC resistance over the test time. As described in the previous section, both responses remained around their initial values at the beginning of the test, but the TDR reflection coefficient showed a gradual increase as the solder joints were stressed. In order to examine whether this increase was caused by physical cracking within the solder joint, the creep test was stopped at 841 min when the TDR reflection coefficient showed an increase of approximately 16 mU from its initial value. This partially degraded sample was potted in epoxy and cross-sectioned on a plane orthogonal to the long axis of the filter, as shown in Figure 7.

Figure 8 shows a scanning electron microscope (SEM) image taken after cross-sectioning. The image revealed that a partial crack initiated at the side where the shear force was applied and propagated towards the center, which coincided with the direction of the applied shear force. This partial crack was responsible for the changes in the TDR reflection coefficient, and, therefore, produced a gradual RF impedance increase as the crack propagated further towards the interior.
On the other hand, the opposite side of the solder joint was still intact, which provided an adequate signal path for the DC current to travel through. The change in the TDR reflection coefficient and the corresponding partial crack were observed from other degraded samples over multiple trials, though the actual values of the initial TDR reflection coefficient and the DC resistance varied depending on the size and shape of the solder fillet.

Discussion

For the eutectic tin-lead solder joints, the side of the solder joint to which the shear force was applied underwent deformation, and became vertically flat. Also, the entire solder joint moved slightly on the solder pad along the direction of the applied shear force. On the other hand, the SAC305 solder joints exhibited less deformation, but the entire solder joint moved farther than the eutectic tin-lead solder joint did. In those samples with an abnormally large amount of solder, the displacement sometimes caused a SAC305 solder joint to touch the ground plane of the circuit board during creep testing. This led to a sudden increase in the TDR reflection coefficient even before a DC open circuit was observed. In spite of the different material characteristics of each solder alloy, RF impedance failure precursors were still detectable prior to changes in DC resistance during solder joint degradation.

In addition to providing interconnect failure precursors, RF impedance analysis offers advantages as a research tool for studying intermediate stages of interconnect failure progress prior to complete failure. Figure 9(a) shows another cross-sectional image of a degraded eutectic tin-lead solder joint under creep testing. In order to observe the crack propagation direction, the cross-sectioning direction was chosen to be parallel to the applied shear force direction. A partial crack initiated between the bottom of the end-termination of the component and the solder pad and then propagated towards the interior of the solder joint. Figure 9(b) provides a close-up image of the demarcated area in Figure 9(a), which allows the inspection of solder joint microstructure. A band of enlarged grains was observed around the partial crack path and beyond, along its projected path. The remainder of the cross-sectional area showed a mixture of the Pb-rich (light) and the Sn-rich (dark) phases as typically seen in the microstructure of intact solder. This band was also observed in other degraded solder joints, such as shown in Figure 8. It represents localized accumulating damage caused by thermo-mechanical stresses under creep testing, and may be an indication of recrystallization. The geometry and the localization of the changes to the microstructure strongly suggest that this will serve as the future crack path. Thus, RF impedance monitoring provides a means for systematic investigation of damage accumulation and failure mechanisms under a variety of stress conditions.

Conclusions

The ability of RF impedance analysis to provide interconnect failure precursors during thermo-mechanical loading has been demonstrated for two different solder alloys. A test vehicle was developed to allow direct comparison of RF impedance and DC resistance during the degradation of solder joints. The solder alloys investigated included eutectic tin-lead and SAC305 lead-free solder, which are widely used by the electronics industry. It was shown that regardless of the solder alloy, the TDR reflection coefficient provided interconnect failure precursors under thermo-mechanical loading conditions, while the DC resistance did not show any indications of degradation until complete solder joint separation. Failure analysis revealed that a partial crack
within a degraded solder joint was responsible for the increase of the TDR reflection coefficient. Therefore, RF impedance can serve as a dependable indicator of interconnect degradation, allowing prediction of impending failure prior to loss of DC continuity.

RF impedance analysis can serve as a real-time monitor of interconnect integrity. In order to detect changes in RF impedance, this technique can be incorporated into sensing circuitry that is either located on a circuit board or in external diagnostic hardware. Since the changes in RF impedance leading up to failure are gradual in nature, the damage level associated with interconnect degradation can be related to changes in RF impedance. In-situ measurement of RF impedance can thus provide a non-destructive means to assess the health of a system in real-time. This would allow condition-based maintenance, thereby increasing product availability. The resulting reductions in unplanned downtime could produce substantial savings in operational, repair, and liability costs.

Future work on this topic will involve identification of the sensitivity of this technique by relating crack length to RF impedance, and testing of more complex test vehicles and interconnect structures under environmental and operational loading conditions.

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References