

Use of the Skin Effect for Detection of Interconnect Degradation

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Abstract

Measurements based on DC resistance have traditionally been used to monitor the reliability of electronic products. Unfortunately, DC resistance is not useful for detecting intermediate stages between a short and an open, such as a partially degraded interconnect. Under cyclic loading conditions, interconnect degradation is caused by fatigue cracking, which often initiates at the surface where the strain range is maximized. At high operating frequencies, signal propagation is concentrated at the circumferential region of an interconnect due to the skin effect. Therefore, RF impedance analysis offers a more sensitive means of detecting interconnect degradation than DC resistance. The skin effect also has implications for the reliability of electronics used in applications such as radar and telecommunications. The use of higher frequencies will make these circuits increasingly susceptible to performance degradation as a result of small cracks or deformation that would go unnoticed in lower frequency applications.

This study demonstrates applications of the skin effect to detect interconnect degradation. Mechanical fatigue tests have been conducted with an impedance-controlled circuit board on which a surface mount component was soldered. During solder joint degradation, simultaneous measurements were performed of DC resistance and the time domain reflectometry (TDR) reflection coefficient as a measure of RF impedance. Two TDR reflection coefficients with different frequency ranges were monitored to evaluate the effect of frequency range on the sensitivity of RF impedance to mechanical degradation. The TDR reflection coefficients were consistently observed to increase in response to early stages of solder joint cracking, while the DC resistance remained constant until the solder joint was completely separated. The TDR reflection coefficient measured over a higher frequency range

responded earlier than one with a lower frequency range. This demonstrates that as signal frequencies increase, smaller cracks are capable of producing detectable amounts of signal integrity degradation.

Key words: Impedance, Interconnect, Reliability, Time domain analysis

Introduction

Since most products today depend to some extent for their functionality on electronics, their reliability is dependent upon that of the electronics [1]. During system operation, electronics are exposed to a variety of possible loading conditions such as temperature or power excursions, shock, and vibration. Interconnects, such as solder joints, printed circuit board traces, component leads, and connectors, are vulnerable to these loading conditions and are susceptible to failures by mechanisms such as fatigue, creep, corrosion, and mechanical over-stress. Regardless of the failure mechanism, interconnect degradation often initiates at the surface and propagates inward as shown in Figure 1.

The electronics industry typically evaluates the reliability of electronic interconnects by monitoring the DC resistance through daisy-chained circuits or dummy components. With appropriate sampling techniques, DC resistance can provide an accurate indication of an open or a short circuit [2], but it is not useful for detecting intermediate stages between them, such as a partially degraded interconnect. Kwon *et al.* [3][4] have previously reported the use of RF impedance as an improved means for monitoring interconnect reliability. Due to the skin effect, a phenomenon wherein signal propagation at high frequencies is concentrated near the surface of a conductor, RF impedance exhibits increased sensitivity to small cracks initiated at the surface of an interconnect.

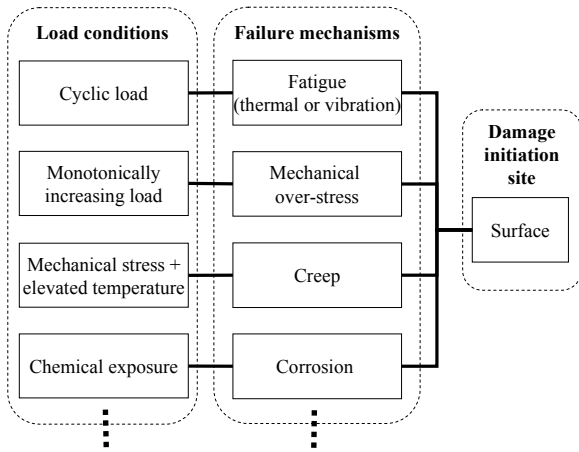


Figure 1: Typical causes of solder joint failure

This paper describes the principles underlying the RF measurement approach and demonstrates the benefits of using this method to detect interconnect degradation. Results are presented from mechanical fatigue tests performed on an impedance-controlled circuit board containing a surface mount component. Simultaneous measurements were made of DC resistance and the TDR reflection coefficient over two frequency ranges. The sequential probability ratio test (SPRT) was applied to each of these data streams and used to determine failure precursors; i.e., a detectable event or a series of events associated with interconnect degradation, such as a shift in the mean of a monitored parameter. During fatigue testing, the failure precursors of the TDR reflection coefficients were identified and compared with that of the DC resistance in order to evaluate the effect of frequency range on the sensitivity to mechanical degradation.

The skin effect and detection of interconnect degradation

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 [5]. As shown in equation (1), the skin depth, δ , is directly related to the frequency, f , and the resistivity of the conductor, ρ :

$$\delta = \sqrt{\frac{\rho}{f \pi \mu}} \quad (1)$$

where μ denotes the material's permeability.

Due to the skin effect, the current density falls off exponentially with distance from the surface of a conductor. More than 99% of the current is concentrated within 5 skin depths from the surface. Figure 2 shows the current densities of eutectic tin-lead and copper over distance from the surface of a conductor calculated using equation (1) at a frequency of 1 GHz. Considering that five skin depths for eutectic tin-lead is about 30 micrometers and that the typical diameter of a solder ball (such as one might find under a ball grid array component) is about 300 micrometers, at 1 GHz most of the current is concentrated within 20% of the periphery of the solder ball. Typical surface mount technology (SMT) components have solder fillets that are even wider than this. Due to this surface concentration of current, high frequency signals are more sensitive than DC resistance to physical changes at the periphery of a solder joint, such as a crack.

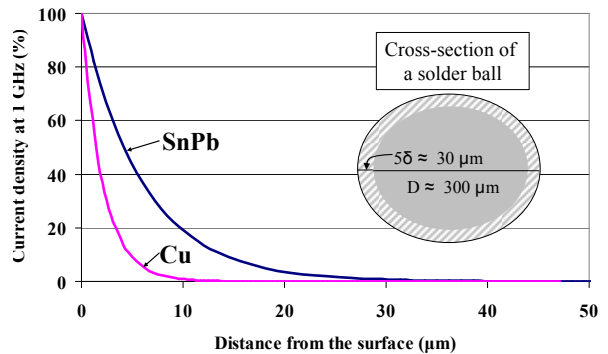


Figure 2: Current density variation with depth

Time domain reflectometry (TDR) can be used to measure impedance discontinuities as discrete peaks with respect to their positions in the circuit, which is useful in identifying fault locations. A TDR measurement is conducted by injecting a pulse or waveform into a circuit and monitoring the reflected voltages due to impedance discontinuities within the circuit, and the round-trip transit time to the location of these discontinuities. A reflection coefficient (Γ) is often used to report the magnitude of a TDR measurement. It is the ratio of the reflected voltage to the signal voltage transmitted from the same port, and it is expressed as shown in equation (2).

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (2)$$

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

In this study, the TDR reflection coefficient obtained from a network analyzer was used as a measure of RF impedance. For TDR reflection coefficient measurement, a network analyzer sweeps and collects the reflection coefficients across the frequency range defined by the user and then applies an inverse fast Fourier transform. Therefore, the time domain measurement using a network analyzer is a composite response over all the frequencies monitored. According to equation (1), as the signal frequency rises the skin depth decreases, leading one to expect an increase in the sensitivity to interconnect degradation. In order to compare the sensitivities of different frequency ranges to solder joint degradation, two TDR reflection coefficients over two frequency ranges, as well as the DC resistance, were continuously monitored using the SPRT until the solder joints exhibited a DC open circuit.

The SPRT is a statistical hypothesis test that determines whether the current test data falls into the probability density distribution of the training data that serves as a baseline [6][7]. In order to detect anomalies in the current test data, the SPRT continuously calculates an SPRT index, which is a function of the current test data, and the statistical parameters of the training data. The SPRT then compares the SPRT index with the lower and upper threshold limits, which are functions of the probability of false positives and false negatives and are thus related to detection sensitivity. When the SPRT index exceeds the threshold limits, the SPRT can trigger an alarm, which indicates the test data has deviated from the initial values. Therefore, the SPRT can help identify anomalous changes in the monitored parameters, such as TDR reflection coefficient and DC resistance.

Experimental setup

A test circuit was developed to simultaneously monitor the TDR reflection coefficients over two ranges and the DC resistance, as shown in Figure 3. The test circuit consisted of an impedance-controlled circuit board, two bias-tees, a Wheatstone bridge, and a vector network analyzer. An SMT low pass filter was connected mechanically and electrically to the circuit board using two solder joints. The bias-tees combined or extracted the DC

and the RF signals in order to allow for simultaneous monitoring of the TDR reflection coefficients and DC resistance using the vector network analyzer and the Wheatstone bridge, respectively. All connections were made using RF cables, which had a characteristic impedance of 50 Ohms.

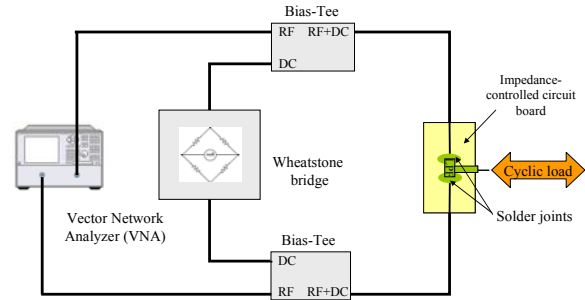


Figure 3: Block diagram of fatigue test circuit

An MTS Tytron 250 was used to apply a cyclic shear force to the low pass filter in order to generate fatigue failures of the solder joints. 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 reflection coefficients over two frequency ranges, respectively. During a fatigue test, both instruments were externally controlled to automate the acquisition of data. In order to identify any deviation, the SPRT was used to analyze the responses and trigger an alarm if it detected any anomalies.

Test conditions

A cyclic shear force was applied to the component (the low pass filter) in the form of a sinusoidal waveform, with an amplitude of 10 N and a frequency of 0.25 Hz, superimposed on a steady-state offset force of 30 N, as shown in Figure 4. The offset force maintained contact between the component and the load transducer throughout the entire fatigue cycle. A ceramic material was inserted to prevent electrical contact between the component and the transducer. The application of the cyclic shear force was continued until it resulted in a DC open circuit or until the TDR reflection coefficients increased significantly.

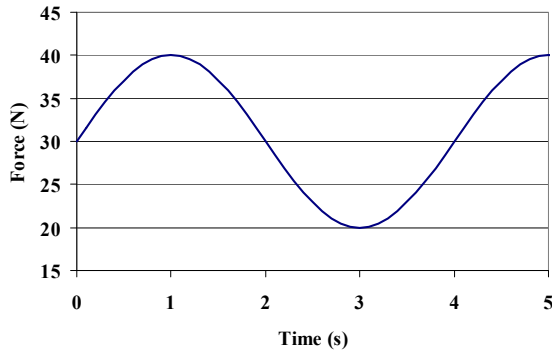


Figure 4: Cyclic shear force profile

In order to examine the relationship between the frequency ranges of the TDR reflection coefficients and their respective sensitivities to interconnect degradation, the TDR reflection coefficients over two different frequency ranges were monitored: 500 MHz to 6 GHz, and 2 GHz to 6 GHz. The former was consistent with the frequency range used in previous studies by the authors, while the latter was restricted to the upper frequencies contained in the first range. Since the cut-off frequency of the low pass filter was 6.7 GHz, the filter acted as a conductor for both frequency ranges.

During solder joint degradation, the DC resistance and the TDR reflection coefficients over two frequency ranges were collected every 30 seconds. After the conclusion of a fatigue test, the SPRT was applied to the TDR reflection coefficients as well as the DC resistance in order to detect failure precursors among the monitored parameters. The data points from 0 to 200 minutes of each parameter in each test were selected as training data for the SPRT, representing the healthy state of the interconnects. In order to reduce the effect of noise on the test data, the SPRT required at least 5 consecutive detections to trigger an SPRT alarm, which was considered as a failure precursor.

Results

Figure 5 shows the results of a fatigue test. It compares the sensitivity to interconnect degradation between the TDR reflection coefficients over two frequency ranges and the DC resistance.

At 762 minutes, the test was concluded due to a DC open circuit resulting from the cyclic shear force. At the beginning of the test, all the monitored parameters stayed at their initial values. Over the duration of the test, the DC resistance remained near its initial value until the final minute, when it increased suddenly to indicate an open circuit. Although the measurement resolution for the DC resistance was enhanced by the use of a Wheatstone bridge, the SPRT could not detect failure precursors in the DC resistance prior to the failure. In contrast, the TDR reflection coefficients did provide early indications of the impending solder joint failure.

As the test progressed, the TDR reflection coefficient with the higher frequency range exhibited a gradual increase, and its slope became steeper towards the end of the test. The SPRT detected a failure precursor at 400.5 minutes, which corresponded to about 53% of the total lifetime. Similarly, the TDR reflection coefficient with the lower frequency range also showed a gradual but slower increase than the one with higher frequency range. The SPRT detected a failure precursor at 630.5 minutes, which was still earlier than the DC open circuit. In general, the same behavior of the TDR reflection coefficients and the DC resistance was repeatedly observed over multiple trials.

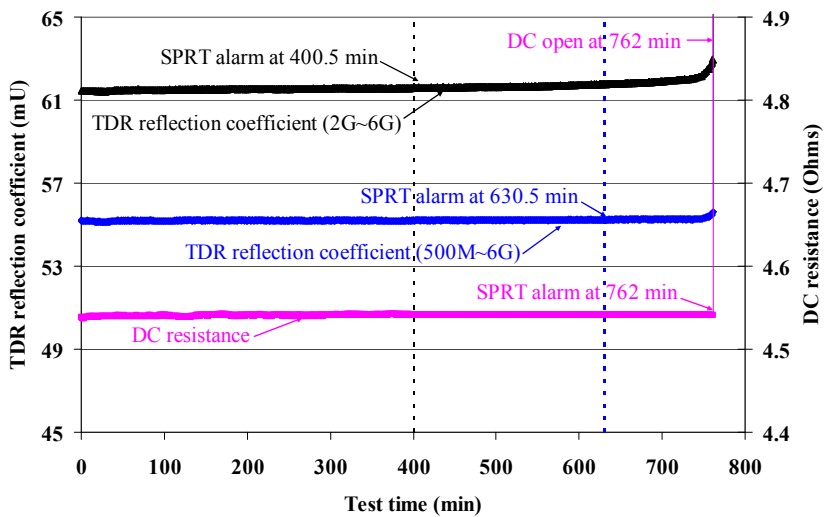


Figure 5: Fatigue test results with failure precursor detection using the SPRT

Conclusions

This study demonstrated that as signal frequencies increase, RF impedance becomes more sensitive to mechanical degradation of an

interconnect. Fatigue tests were conducted to examine the effect of frequency range on the sensitivity of RF impedance to mechanical degradation and to compare the RF responses with DC resistance. Two TDR reflection coefficients, one with a lower frequency range and the other with a higher frequency range, and the DC resistance were simultaneously monitored during solder joint degradation. The SPRT was used to identify failure precursors in the monitored parameters. Regardless of the monitored frequency ranges, the RF impedance provided failure precursors in response to the mechanical degradation of the solder joints, while the DC resistance did not show any indication of degradation until complete solder joint separation. The comparison between the frequency ranges of RF impedance indicated that the higher frequencies were more sensitive to interconnect degradation that initiated from the surface due to the skin effect.

These test results imply that the TDR reflection coefficient is a useful and effective means for monitoring interconnect degradation of an electronic product. DC resistance, which has been traditionally used by the electronics industry, often responds too little (for example, changes in DC resistance are often obscured by the environmental noise in a real life situation) or too late (for example, after the crack is large enough to result in a DC open circuit). Thus, health monitoring using DC resistance measurements would not be expected to provide early indications of interconnect degradation, whereas RF impedance would allow users to perform condition-based maintenance before the degradation results in detrimental consequences to the electronic product. This would help reduce the occurrence of product failure, and thus improve the operational availability of electronic systems.

Another implication of these findings is that as the characteristic frequencies of transmitted signals increase beyond several hundred megahertz, the performance of the product will be increasingly sensitive to even minor levels of interconnect damage. Hence, reliability assessments based on DC resistance monitoring are likely to overestimate the lifetime of electronic assemblies used in applications such as radar and telecommunications.

The surface concentration of high frequency signals resulted in the increased sensitivity of RF impedance to interconnect degradation. Ideally, the sensitivity should exhibit a quadratic increase as the signal frequency increases according to equation (1). However, in a real life situation, as signal frequency increases, the immunity of high frequency signals to electro-magnetic interference is reduced. There is

also the issue of how stable the impedance is as frequency goes much higher. Therefore, an appropriate frequency range needs to be chosen depending upon the minimum crack size to be detected and the electrical characteristics of the sample to be monitored and the measurement system.

Future work on this topic will involve an investigation of the minimum detectable crack size using RF impedance monitoring, and testing of more complex test vehicles and interconnect structures under a variety of environmental and operational loading conditions.

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