Non-Destructive Sensing of Interconnect Failure Mechanisms Using Time Domain Reflectometry

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

Abstract—This paper presents time domain reflectometry (TDR) as a non-destructive sensing method for interconnect failure mechanisms. Two competing interconnect failure mechanisms of electronics were considered: solder joint cracking and solder pad cratering. A simple theoretical analysis is presented to explain the effect of each failure mechanism on the TDR reflection coefficient. Mechanical fatigue tests have been conducted to confirm the theoretical analysis. The test results consistently demonstrated that the TDR reflection coefficient gradually decreased as the solder pad separated from the circuit board, whereas it increased during solder joint cracking. Traditional test methods based on electrical resistance monitoring cannot distinguish between failure mechanisms, and do not detect degradation until an open circuit has been created. In contrast, the TDR reflection coefficient can be used as a sensing method for the determination of interconnect failure mechanisms as well as for early detection of the degradation associated with those mechanisms.

Index Terms—Time domain reflectometry, Interconnection, Reliability, Impedance, Fatigue

I. INTRODUCTION

T
ime domain reflectometry (TDR) is a measurement technique useful for characterizing and localizing changes in impedance of a transmission line or an interconnect. It has been used for a variety of sensing applications, such as for characterizing non-uniform transmission lines [1], locating faults within a wiring system [2], sensing liquid levels [3], and characterizing material properties [4]. Kwon et al. [5] first presented the use of TDR to detect early stages of interconnect degradation. Due to the skin effect, a phenomenon wherein signal propagation at high frequencies is concentrated near the surface of a conductor, small physical changes, such as a crack initiated at the surface of an interconnect, provide a detectable increase in the TDR reflection coefficient, while DC resistance-based techniques, including event detectors, did not exhibit any early changes prior to the interconnect failure. Failure analysis on the partially degraded interconnects revealed that the early increase in the TDR reflection coefficient was due to a crack propagating within the interconnect. Thus, TDR can serve as an early indicator of interconnect degradation.

A TDR measurement is typically reported as a reflection coefficient (Γ) and is made by launching a pulse or a step into the circuit and observing the reflections caused by impedance mismatches with the characteristic impedance of the circuit [6][7]. The TDR reflection coefficient is a ratio of the incident to the reflected voltage. It is a function of the impedance of the device under test (DUT) and the characteristic impedance, as shown in Equation (1):

\[ \Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_0}{Z_L + Z_0} \]  

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

The sensitivity of \( \Gamma \) to early stages of solder joint cracking stems from an increase in \( Z_L \) due to a crack near the periphery of the solder joint. This leads to an increase of the TDR reflection coefficient. If damage is localized at the solder joint, the characteristic impedance remains unchanged. However, printed circuit assemblies can also fail because of pad or trace separation from the dielectric. These phenomena can be associated with changes of the characteristic impedance, \( Z_0 \) in the equation. Thus, these physical changes can also be expected to alter the TDR reflection coefficient. This paper discusses the ability of the TDR reflection coefficient to non-destructively sense and distinguish the interconnect failure mechanisms of solder joint cracking and pad separation (also referred to as pad cratering) on a circuit board.

II. NON-DESTRUCTIVE IDENTIFICATION OF INTERCONNECT FAILURE MECHANISMS

Electronic products are exposed to various environmental and operational loading conditions, such as temperature cycling, vibration, and mechanical over-stress, that may result in the failure of interconnects or circuit boards. With any of the common loading conditions, interconnect degradation often
initiates from the surface and propagates inward. Due to the skin effect, TDR can non-destructively detect the precursors of interconnect failure by monitoring the changes in impedance at the interconnect. Since the TDR reflection coefficient is also associated with changes in the characteristic impedance of the circuit, it should also be able to detect physical changes of the circuit such as pad or trace separation.

Fig. 1. Test vehicle with a component soldered on a signal plane

Fig. 2. Schematic of a simplified coplanar waveguide structure

Fig. 1 shows a circuit board with a coplanar waveguide structure composed of a signal strip line surrounded by two ground planes on the same surface on a dielectric. This type of transmission line is commonly used for board-level interconnects [8]. The characteristic impedance of a coplanar waveguide is a function of the effective dielectric constant ($\varepsilon_e$), the width of the signal trace ($w$), and the distance between the signal and the ground plane ($s$) as shown in Fig. 2. The functional relationship between these quantities may be written as shown in Equation (2) [8][9]:

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_e}} \ln \left( \frac{1 + \sqrt{k'}}{1 - \sqrt{k'}} \right)$$ (2)

where

$$k' = \frac{\sqrt{4\varepsilon w + 4w^2}}{s + 2w}$$ (3)

Pad separation results in both an increase of the effective distance between the signal and ground plane ($s$) and a decrease of the effective signal plane width ($w$) projected onto the circuit board, which raises the $k'$ value and, consequently, the characteristic impedance ($Z_0$) of the circuit board. According to Equation (1), the TDR reflection coefficient decreases as the characteristic impedance increases. From this analysis, pad separation is predicted to lead to a decrease in the TDR reflection coefficient. Thus, the TDR reflection coefficient should be sensitive to pad separation as well as solder joint cracking during degradation of a circuit board under stress, and the different changes in TDR reflection coefficient should allow for non-destructive identification of the relevant failure mechanisms.

III. EXPERIMENT

In order to examine the ability of TDR to distinguish between interconnect failure mechanisms, a test circuit was developed as shown in Fig. 3. The test circuit included an impedance-controlled circuit board on which a low pass filter was soldered, two bias-tees for the simultaneous monitoring of the TDR reflection coefficient and DC resistance, a Wheatstone bridge for DC resistance measurement, and a vector network analyzer for the TDR reflection coefficient measurement. These components were connected using impedance-controlled RF cables in order to match the characteristic impedance of the test equipment.

Fig. 3. Schematic of the test circuit

The test circuit board, shown in Fig. 4, also had a controlled characteristic impedance of 50 Ohms with an SMA connector on each side. A surface mount technology (SMT) low pass filter (LPF) was soldered on this circuit board using Sn-37Pb solder paste. The cut-off frequency of the low pass filter was 6.7 GHz, and the monitored frequency span for the TDR reflection coefficient was between 500 MHz and 6 GHz. Therefore, the low pass filter acted as a conductor to both the RF and DC signals.

A Wheatstone bridge was incorporated into the test circuit for DC resistance measurement. It not only eliminated environmental influences such as fluctuations of the ambient temperature, but also increased measurement resolution. A Keithley 2010 multimeter was used to monitor the voltage in the Wheatstone bridge circuit, which was converted into DC resistance. An Agilent E8364A vector network analyzer configured with TDR functionality was used to monitor the TDR reflection coefficient during fatigue testing. Each set of TDR measurement data contained a collection of reflection coefficient values over the partial signal path of the circuit board, collected at a particular instant during the fatigue test. In order to monitor changes in both the RF impedance and the DC resistance during interconnect degradation, the TDR reflection coefficients at each potential failure site were extracted and

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compared with the DC resistance by displaying them in a plot as a function of test duration.

![Fig. 4. Test circuit board soldered with a low pass filter](image)

An MTS Tytron 250 was used to apply mechanical load to the SMT filter in the form of a cyclic shear force. The shear force profile was programmed, applied to the body of the component, and monitored during fatigue testing. A strip of alumina was inserted between the metal tip of the force transducer and the component to avoid making electrical contact between the loading system and the circuit.

**A. Test conditions**

A cyclic mechanical shear force was directly applied to the low pass filter in order to produce fatigue failure of the interconnects. An offset force was used to maintain the contact between the component and the force transducer throughout the entire fatigue cycle, and the oscillatory force produced a cyclic loading condition leading to fatigue failure. The shear strength of the solder pad was measured to be about 70 N, and thus the maximum force had to be maintained below the shear strength to generate fatigue failures. Preliminary fatigue tests were performed to identify the offset force levels that result in solder joint cracking and pad separation, respectively, given an amplitude of 10 N and a frequency of 0.25 Hz in a sinusoidal waveform. It was observed that as the offset force increased above 40 N the interconnect failure mechanism shifted from solder joint cracking to pad separation. Considering the fact that a higher offset force typically produced a shorter time to failure, the offset forces for solder joint cracking and pad separation were chosen to be 30 N and 45 N, respectively. Thus, the final cyclic force profile was programmed as a sinusoidal waveform of 10 N amplitude and 0.25 Hz frequency superimposed on the offset force for each case, as shown in Fig. 5.

**IV. RESULTS AND DISCUSSION**

During fatigue testing, instrumental control software was used to instruct the multimeter and the vector network analyzer to collect the DC resistance and the TDR reflection coefficient, respectively, every 30 seconds. During each experiment the TDR responses and the DC resistance were monitored until the cyclic stresses resulted in either a separation of the solder pad from the circuit board or a DC open circuit within the solder joint.

![Fig. 5. Load profile for pad separation failure during fatigue testing](image)

Fig. 6 shows a fatigue test result comparing the TDR reflection coefficient at the solder joint with the DC resistance while the applied cyclic shear force produced solder joint failure due to cracking within the solder. The test was concluded at 524 minutes, at which time a DC open circuit occurred due to solder joint cracking. During the test the TDR reflection coefficient and the DC resistance, calculated from a node voltage in the Wheatstone bridge, were collected every 30 seconds. Both the TDR reflection coefficient and the DC resistance stayed around their initial values during the first few hundred minutes of test time. As the test progressed, the TDR reflection coefficient gradually increased in response to the growth of cracks within the solder joint, while the DC resistance remained the same. At the end of the test, both the TDR reflection coefficient and the DC resistance showed a sudden increase indicating a DC open circuit of the solder joint, as shown in Fig. 7. This behavior of the TDR reflection coefficient during solder joint cracking coincides with the observations described in [5]. Cross-sectional failure analysis consistently confirmed that solder joint cracking was responsible for these failures.

Fig. 8 shows the results of a fatigue test in which the failure occurred due to pad separation from the circuit board. The total duration of the test was 194 min. The DC resistance remained around its initial value throughout the test, as observed during all but the last measurement of the solder joint cracking experiments. The TDR reflection coefficient, however, showed a gradual decrease towards the end of the test, which resulted from the separation of the solder pad from the circuit board.
The test was stopped when contact between the force transducer and the component was lost due to pad separation. In spite of the pad separation, the solder joint still provided a mechanical and electrical connection between the component and the pads. Therefore, in this test neither measurement exhibited a sudden rise that would indicate a DC open circuit at the end of the test.

![Graph showing TDR reflection coefficient and DC resistance during solder joint cracking](image)

**Fig. 6.** TDR reflection coefficient (in milliunits, mU) and DC resistance during solder joint cracking

After the fatigue test, the circuit board was inspected with a scanning electron microscope (SEM) to locate the physical damage that was responsible for the changes in the TDR reflection coefficient. As shown in Fig. 9, the SEM revealed that the solder pad was torn off of the circuit board, a failure known as pad cratering. This phenomenon was responsible for the decrease of the TDR reflection coefficient near the end of the test. Also, the SEM showed that the solder joint on top of the separated pad remained intact, providing an electrical connection, which indicated that the decrease in the TDR reflection coefficient was caused by the increase in the characteristic impedance.

Table 1 summarizes the test results, including the duration of the test, the changes in TDR reflection coefficient measurement before and after the test, and the observed failure mechanisms. These results indicate that TDR can be used to identify interconnect failure mechanisms because the response over time of the TDR reflection coefficient differs for each interconnect failure mechanism. Solder joint cracking led to an increase of the TDR reflection coefficient during solder joint degradation. This behavior was consistently observed under different loading conditions such as fatigue [5] and creep [10], and using different solder alloys including eutectic tin-lead and Sn-3.0Ag-0.5Cu lead free solder [10]. On the other hand, it was found that when a high level of fatigue loading was applied, the TDR reflection coefficient exhibited a gradual decrease, and the interconnect failed due to pad cratering [11]. The present study has validated this initial observation of the effect of pad cratering failure on TDR response; established that this effect is directly associated with the change of characteristic impedance when pad cratering occurs; demonstrated that this response can be readily used to distinguish pad cratering from solder joint cracking; and shown that the pad cratering mechanism can be produced in a repeatable manner when the offset force of fatigue loading is increased. As reported in [12], a failure mechanism transition in surface mount assemblies can occur due to changes in the load level.

This study has shown that TDR can serve as a non-destructive means to consistently distinguish between competing interconnect failure mechanisms. Moreover, TDR can provide useful information for predicting the time to failure of an interconnect exposed to stress. In both interconnect failure mechanisms, changes in the TDR reflection coefficient were gradual in nature, which could be useful as a failure precursor to implement prognostics of interconnect failure.

![Graph showing TDR reflection coefficient and DC resistance during pad cratering](image)

**Fig. 8.** TDR reflection coefficient (in milliunits, mU) and DC resistance during pad cratering

<table>
<thead>
<tr>
<th>Test no</th>
<th>Test time (min)</th>
<th>Changes in TDR (mU)</th>
<th>Failure mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>524</td>
<td>2</td>
<td>SJC</td>
</tr>
<tr>
<td>2</td>
<td>866</td>
<td>2</td>
<td>SJC</td>
</tr>
<tr>
<td>3</td>
<td>974</td>
<td>5</td>
<td>SJC</td>
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<tr>
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<td>191</td>
<td>9</td>
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</tr>
<tr>
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<td>1303</td>
<td>6</td>
<td>SJC</td>
</tr>
<tr>
<td>6</td>
<td>194</td>
<td>-5</td>
<td>PC</td>
</tr>
<tr>
<td>7</td>
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<tr>
<td>10</td>
<td>1210</td>
<td>-3</td>
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</table>

(Note: for failure mechanism “SJC” and “PC” indicate solder joint cracking and pad cratering, respectively.)
The ability of TDR to non-destructively identify interconnect failure mechanisms during cyclic loading has been demonstrated. Previously, it was shown that RF impedance can serve as a non-destructive means to detect early stages of solder joint cracking. During a fatigue test the TDR reflection coefficient gradually increased [5]. In this study, the loading conditions were changed to produce a different failure mechanism, pad cratering. It was revealed that the TDR reflection coefficient gradually decreased as the solder pad separated from the circuit board. This behavior was explained on the basis of a theoretical analysis of the effect of changes in characteristic impedance or impedance of the device under test on the TDR reflection coefficient. Meanwhile, the DC resistance, a traditional measure of interconnect reliability, did not provide early indications of interconnect degradation or allow identification of failure mechanisms during these tests. Therefore, TDR analysis was found to be useful as a prognostic sensing technique to detect early stages of interconnect degradation on printed circuit boards and non-destructively identify interconnect failure mechanisms.

These results imply that analysis based on TDR can provide accurate reliability assessment of electronics exposed to cyclic loading conditions, such as vibration, repeated mechanical shocks or flexure, or thermal cycling. Regardless of interconnect failure mechanisms, the TDR reflection coefficient exhibited early and gradual changes in response to physical degradation of an interconnect. As clock speeds and communication frequencies rise, it may be expected that the performance of electronics will be adversely affected even by partially degraded interconnects due to the skin effect. Thus, the ability to detect physical changes such as small cracks or a small degree of pad separation in the early stages of the degradation process should become increasingly valuable for accurate reliability assessment.

TDR can produce useful information for maintenance of electronics while they are still in service. Not only can TDR be used for early detection of interconnect degradation, but it also provides insight into the physical processes by which failures are being induced before the failure occurs. This application of TDR can eventually allow the user to initiate preventive actions prior to catastrophic failures and to have information about what is degrading. Thus, repair time can be reduced, and ultimately higher product availability can be achieved.

Analysis based on TDR offers great promise for use in prognostics of electronic products. Since the changes in TDR reflection coefficient leading up to failure were gradual in nature, it should be possible to quantify the damage level associated with solder joint cracking or pad separation. Depending on the nature of the changes in the TDR response, the appropriate set of training data and detection criteria can be applied in order to predict the remaining life for either failure mechanism. Regression analysis on the gradual changes of the TDR reflection coefficient paired with goodness of fit calculations is currently being investigated for predicting the remaining useful life of interconnects under controlled cyclic loading conditions. The use of statistical algorithms that can account for the variability of real-life loading conditions should enable an accurate calculation of the remaining useful life of products in the field. Eventually, this technique could enable condition-based maintenance, resulting in improved safety and economic advantages not only for manufacturers but also for users.

V. CONCLUSIONS

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REFERENCES


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