Application Note

Electronic Package Failure Analysis Using TDR

Introduction

Time Domain Reflectometry (TDR) measurement methodology is increasing in importance as a non-destructive method for fault location in electronic packages [1]. The visual nature of TDR makes it a very natural technology that can assist with fault location in BGA packages, which typically have complex interweaving layouts that make standard failure analysis techniques, such as acoustic imaging and X-ray [2], less effective and more difficult to utilize.

In this paper, we will discuss the use of TDR for package failure analysis work. We will analyze in detail the TDR impedance deconvolution algorithm as applicable to electronic packaging fault location work, focusing on the opportunities that impedance deconvolution and the resulting true impedance profile opens up for such work.

TDR Fundamentals

TDR was initially developed for fault location of long electrical systems, whereas, Optical TDR (O-TDR) primarily applies to fault location in optical fiber.

TDR is very similar to X-ray and acoustic imaging techniques in that it sends the signal to the Device Under Test (DUT) and looks at the reflection to obtain the information about the DUT. The difference between X-ray or acoustic imaging and TDR is in the type of signal and the type of propagation media for the signal. X-ray and acoustic imaging use X-ray and acoustic stimuli correspondingly, propagating through the free space and acoustic coupling media to the DUT, whereas TDR uses fast-electrical-step stimulus, delivered to each trace in the DUT via electrical cables, probes, and fixtures. A direct electrical contact between the TDR instrument and the DUT is required to perform the measurement. In addition, not only the signal, but also the ground contact must be provided in order for the TDR signal to provide meaningful information about the DUT (fig.1). Without a good ground contact, the TDR signal will not have a good current ground return path, and the TDR picture will be extremely hard to interpret.

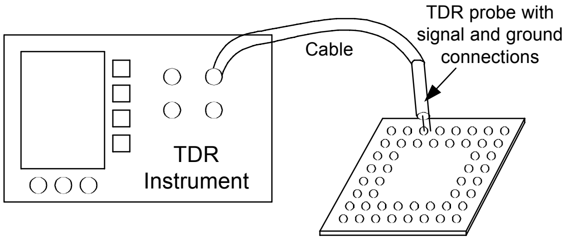

Figure 1. TDR oscilloscope measurement setup. Both signal and ground connection are necessary in order for the TDR signal to provide meaningful information about the DUT

A typical TDR oscilloscope block diagram is shown in figure 2.

The fast-step-stimulus waveform is delivered to the DUT via electrical cable, probe, and fixture interconnects. The waveform reflected from the DUT is delayed by two electrical lengths of the interconnect between the DUT to the TDR oscilloscope, and superimposed with the incident waveform at the TDR sampling head (fig. 2). The incident waveform amplitude at the DUT is typically half the original stimulus amplitude (V) at the TDR source. The smaller DUT incident waveform amplitude is due to the resistive divider effect between the 50 Ω resistance of the source and 50 Ω impedance of the coaxial cables connecting the TDR sampling head and the DUT.

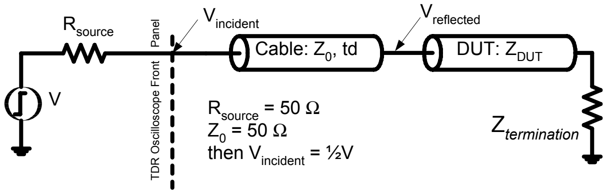

Figure 2. TDR oscilloscope equivalent circuit.

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As the reflected signal is observed in the TDR, one can choose a voltage, reflection coefficient, or impedance mode on the TDR oscilloscope. Either one of these outputs represents the signature of the DUT.

TDR does not provide an optical image of the package, but rather an electrical signature of the trace in the package. Because of the nature of the information that TDR provides, it is important to be aware of typical TDR signatures that correspond to simple package failures, such as a short or an open connection (fig. 3).

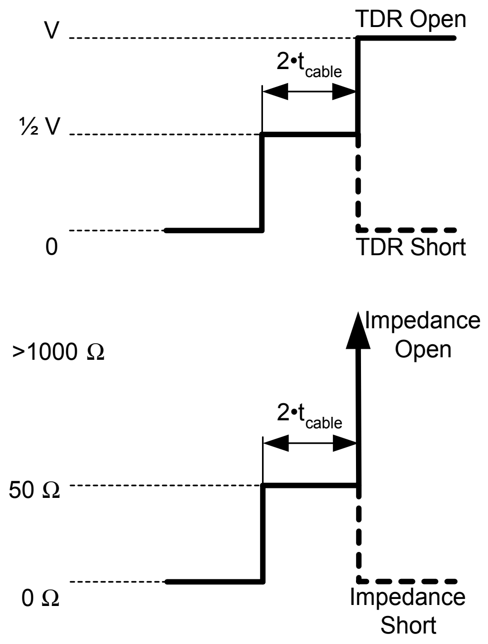


Figure 3. Open and short connection TDR and impedance profile signatures. V is the full voltage amplitude of the TDR step source; t_{cable} is the electrical length of the cable and probe interconnecting the TDR oscilloscope and the DUT.

TDR measurements always display the round trip electrical delay for the cables, fixtures, and DUTs, which is why figure 3 displays twice the delay of the cable interconnecting the TDR instrument to the DUT.

The faster the rise time that the TDR interconnect can deliver to the package under test, the smaller the size of the discontinuities that can be resolved with a TDR oscilloscope. Available TDR instrumentation provides very fast rise times; reflected signal rise times of the order of 25-35 ps can be observed at the TDR oscilloscope. However, poor quality cabling and fixturing can quickly degrade the TDR instrumentation rise time and decrease the instrument resolution. We will discuss the TDR measurement accuracy issues in further detail in the section entitled TDR Accuracy Considerations. Additional information about TDR measurement technology and TDR oscilloscopes can be found in references [3] and [4].

TDR Multiple Reflection Effects and the True Impedance Profile

One of the limitations of TDR is the effect of multiple reflections, which is present in multi-segment interconnect structures, such as an electrical package. The accuracy of the DUT signature observed at the TDR oscilloscope is dependent on the assumption that at each point in the DUT, the incident signal amplitude equals the original signal amplitude at the probe-to-DUT interface. In reality, however, at each impedance discontinuity, a portion of the TDR incident signal propagating through the DUT is reflected back, and only a portion of this signal is transmitted to the next discontinuity in the DUT. In addition, the signal reflected back to the scope may re-reflect and again arrive at the next discontinuity at the DUT. These so called "ghost" reflections are illustrated on the lattice diagram in figure 4.

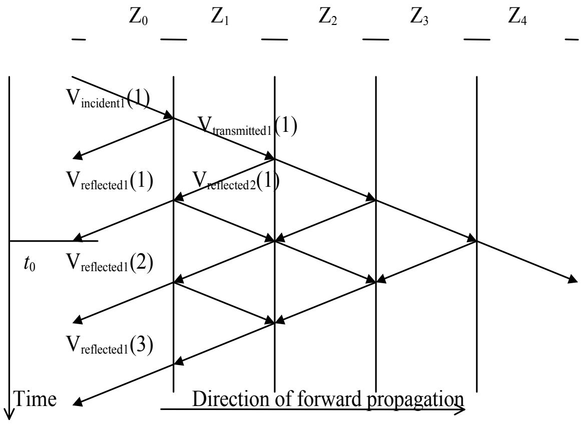
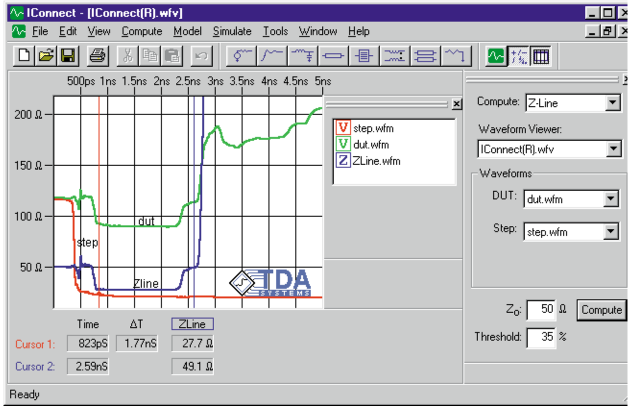


Figure 4. Lattice diagram of TDR waveform propagating through a DUT with multiple impedance discontinuities.

As a result of these re-reflections, the signature of the DUT becomes less clear, and additional processing is required using the impedance deconvolution algorithm ([5] and [6]), which is currently not available in TDR oscilloscopes. The impedance deconvolution algorithm deconvolves the multiple reflections from the TDR waveform and provides the *true impedance profile* for the DUT, significantly improving the clarity of the DUT signature and simplifying further analysis of the TDR data.

For example, in figure 5 the DUT waveform (dut.wfm) is the TDR waveform of a board trace, going through several impedance discontinuities. The Zline waveform (Zline.wfm) is the true impedance profile waveform computed from the TDR data. It is obvious from the true impedance profile waveform that it is open-ended at the far end, because its impedance goes to infinity at about 2.75 ns. The TDR waveform, on the other hand, appears to continue re-reflecting back and forth at that time, which in effect is an artifact of multiple reflections. The true impedance profile provides an exact location of the open in the DUT, whereas the TDR waveform by itself provides confusing information about the location of this open. Therefore, the impedance profile provides more accurate impedance readouts and more precise information about the position of possible short and open failures.

The waveform step.wfm is the reference waveform, acquired by disconnecting the TDR probe from the DUT and shorting the signal tip of the probe to ground on a simple conductive metal plate (short reference) or leaving the probe open in the air for the measurement (open reference). Such reference information is required in order to compute the true impedance profile using the impedance deconvolution algorithm, and to properly define the DUT measurement reference plane.



Compute: Z-Line

Waveform Viewer: IConnect(R).wfv

Waveforms

DUT: dut.wfm

Step: step.wfm

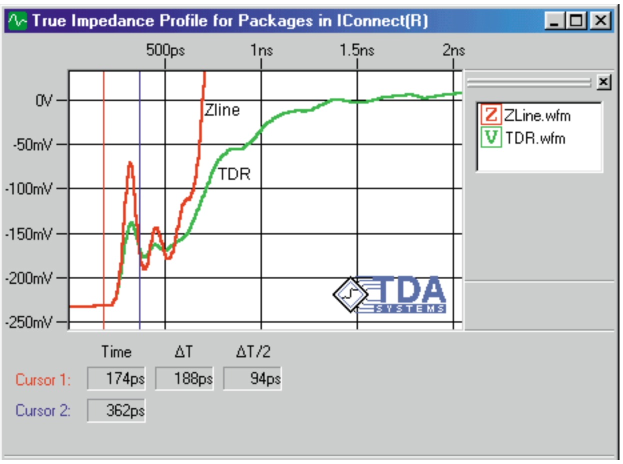
Z_0: 50 Ω

Threshold: 35 %

	Time	ΔT	ZLine
Cursor 1:	823pS	1.77nS	27.7 Ω
Cursor 2:	2.59nS		49.1 Ω

Figure 5. True impedance profile (Zline.wfm) vs. raw TDR data (dut.wfm). Waveforms are offset for display purposes.

Similarly, if a failure analysis technician were looking for an open failure in an electrical package, TDR data by themselves would probably not have been sufficient to locate the position of the failure (fig. 6). In addition, the impedance profile, being an exact signature of the DUT, is relatively easy to correlate to different layers in a BGA package. Such correlation is practically impossible with a TDR waveform alone.



	Time	ΔT	ΔT/2
Cursor 1:	174ps	188ps	94ps
Cursor 2:	362ps		

Figure 6. True impedance profile (Zline.wfm) vs. the raw TDR waveform (TDR.wfm) for a BGA package. The true impedance profile provides much more accurate information about the failure location.

An additional advantage that the true impedance profile provides is that it is very easy to evaluate capacitance or inductance of an impedance profile segment using the following equations:

$$C = \frac{1}{2} \cdot \int_{t_1}^{t_2} \frac{1}{Z(t)} dt \qquad L = \frac{1}{2} \cdot \int_{t_1}^{t_2} Z(t) dt \qquad (1)$$

The type of discontinuity (inductive or capacitive) that we observe in the impedance profile, can also be easily identified — a "dip" in the impedance profile corresponds to an capacitive discontinuity, and a "peak" corresponds to an inductive discontinuity. Being able to estimate the value of capacitance or inductance for any given segment can be a significant help in understanding which package segment is being analyzed and in locating the failure more accurately.

TDR Accuracy Considerations

Before discussing package failure analysis techniques using TDR in further detail, it is imperative to note the importance of obtaining a good quality TDR measurement and a clean impedance profile. Without a good TDR measurement for the DUT and the reference, the true impedance profile is likely to be computed incorrectly, and both TDR data for the DUT and the true impedance profile will provide a confusing picture.

TDR is delivered to the DUT via electrical cable, probe, and fixture interconnects. The quality of these interconnects is the key to obtaining a good measurement. As noted before, poor quality cabling and probes can degrade the TDR rise time and decrease the resolution of the instrument. In addition, when computing the impedance profile, it is necessary to have a clean reference short or open waveform; without a good reference, we are not likely to get a clear signature of the DUT. Because of these factors, good quality microwave probes and cables are required to obtain a good quality TDR measurement.

Fixtures, probes, and probing stations for package failure analysis work are available from various manufacturers. A full-featured failure analysis probing station can provide easy viewing and access to the package with a probe, and enable a failure analyst to perform at-temperature analysis of the package failures.

Failure Analysis Goals and Methods

The goal and the task of the failure analyst is to determine *whether* there is a possible connection failure in the given package trace, and what the *exact position* where the failure has occurred. Once the position of the failure is determined, further analysis can be performed to determine the physical cause and the nature of the failure, possibly with destructive analysis methods.

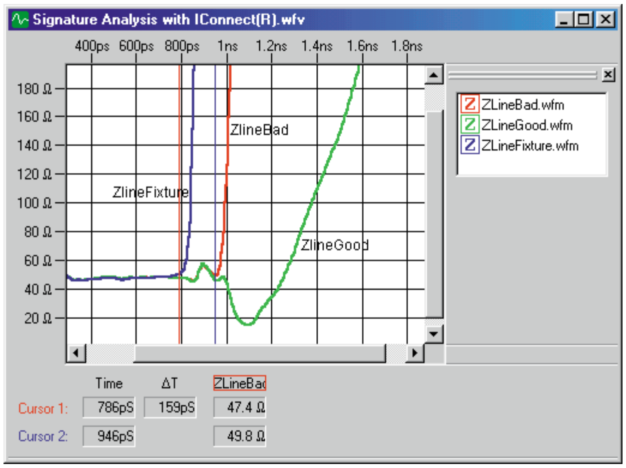
Typical approaches that can be used to determine whether there is a failure present are *signature analysis*, where the package trace true impedance profile data are analyzed for known failure signatures, and *comparative analysis*, where the package trace data are compared to the data of a trace in a known good package. Both approaches will be applied to the true impedance profile data obtained from the TDR using the impedance deconvolution algorithm as it is implemented in TDA Systems' IConnect® software.

The true impedance profile provides a much clearer picture of the failure type, and also enables the user to easily determine the exact position of the failure in an electrical sense, i.e., in terms of electrical length of the interconnect in picoseconds. Additional analysis must be performed to determine the *physical* location (in millimeters or milli-inches) of the failure with the goal of locating the package element that is failing. The true impedance profile provides the user with a way to correlate the TDR data to the specific layers in the package, as well as provide an estimate of a constant that would allow the user to convert the electrical length in picoseconds into physical lengths in milliinches.

Signature analysis

In the true impedance profile, open and short failures can be easily identified as 0 Ohm impedance readout for the short and very high (1000 Ohms or more) impedance readout for the open (fig.3). The exact electrical position of a short or an open can be easily identified in the true impedance profile, even in the presence of multiple reflections, as previously described.

In the following example (fig. 7), the known good BGA package (ZlineGood.wfm) was analyzed alongside a suspect package (ZlineBad.wfm). The fixture impedance profile (ZlineFixture.wfm) is shown for reference. The known good package impedance profile ends with a large capacitive dip, corresponding to the input package capacitance. An open failure is clearly observed in the BGA package at about 80 ps inside the package (160 ps round trip delay).



	Time	ΔT	ZLineBad
Cursor 1:	786pS	159pS	47.4 Ω
Cursor 2:	946pS		49.8 Ω

Figure 7. Signature analysis of a BGA package failure using the true impedance profile in IConnect software.

So called "soft" failures, i.e., partly shorted or partly open leads, can also be identified using the signature analysis, but their impedance profile and TDR signatures must be identified beforehand. The only alternative to knowing the soft failure signature beforehand is to observe the changes in capacitance of the known good device compared to the failing device.

TDR has specific signatures for the open and short connections, as shown in figure 3, and can also be used for identifying the failures. However, in multi-segment structures, such as BGA packages, the exact location of the failure can be difficult to determine because of the multiple reflection effects.

Comparative analysis

Comparative package failure analysis, as the name implies, relies on comparison of the known good waveform to the suspect waveform. Even though some discrepancy between different measurements may still be observed due to measurement repeatability, the comparative analysis utilizing the true impedance profile waveforms, computed using IConnect software, yields very quick and intuitive results.

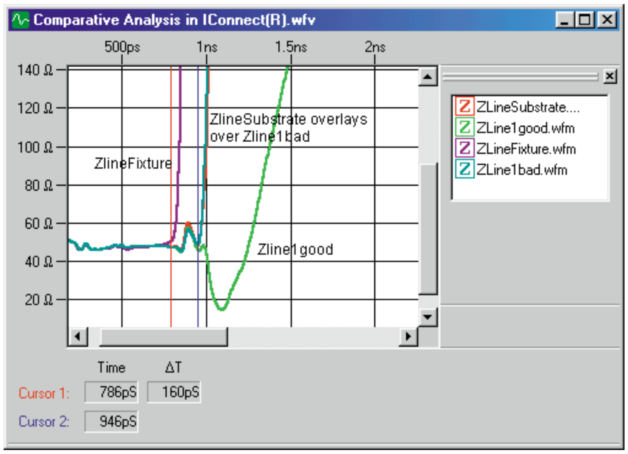
Consider the following example. In figure 7, the package failure is identified as an open failure. In figure 8, the analysis is continued by comparing the failed waveform to the package substrate waveform only, without connection to the die. The challenge is to determine what package component is failing based on this comparative analysis. Because the failed impedance profile waveform overlays directly over the substrate waveform, it is easy to deduce that the likely failure source is the broken connection between the package and the die. Again, the large capacitive dip is due to the input capacitance of the die.

Based on this analysis, a failure analyst can focus on the connection to the die area, and use additional failure analysis techniques to determine the physics of the failure.

An important issue when performing comparative analysis is measurement repeatability. Following good general measurement practices, such as:

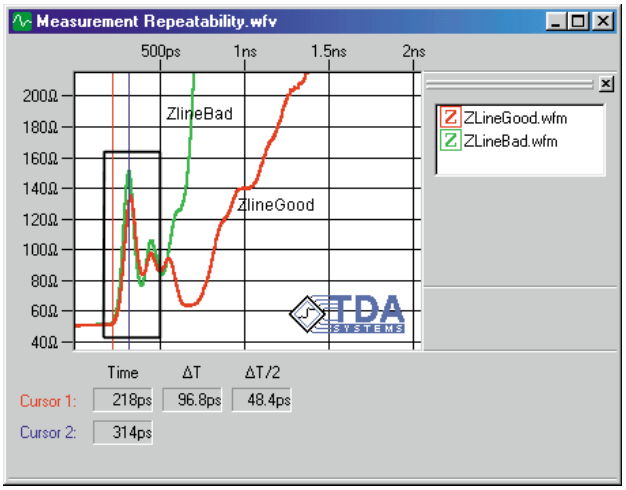
- maintaining TDR instrument calibration
- keeping the instrument well-warmed in a lab with constant ambient temperature
- maintaining the probe or cable position and spacing between the probe signal and ground during the measurement

will enable the analyst to minimize any non-repeatability errors. However, a failure analyst must be aware that small differences between different impedance profiles may actually result from measurement non-repeatability, rather than failures in the package under test. Whether it is the failure or a measurement repeatability issue can be determined much easier with the use of the true impedance profile. For example, because of the differences between the good package impedance profile (ZlineGood.wfm) and bad package impedance profile (ZlineBad.wfm) in the outlined region of figure 9, a failure analyst may view the differences between the good and bad waveforms in the selected region as the cause for the failure observed in the later portion of the impedance profile. However, because we are working with the impedance profile and not the TDR waveform, any effect of the reflections in the selected region on the rest of the impedance profile waveform is minimal. With that in mind, the differences between the two impedance profiles are too small to be viewed as the cause of the failure. And, one can comfortably conclude that the failure occurred in the later portion of the package (in this case, again, it is a failure of the package-to-die connection.)



	Time	ΔT
Cursor 1:	786pS	160pS
Cursor 2:	946pS	

Figure 8. Comparative analysis for a BGA package. The “bad” impedance profile waveform clearly indicates an open failure signature. Comparing it to the package substrate waveform only without connection to the die, allows pinpointing the likely failure source — a broken connection to the die.



	Time	ΔT	ΔT/2
Cursor 1:	218ps	96.8ps	48.4ps
Cursor 2:	314ps		

Figure 9. Measurement repeatability considerations.

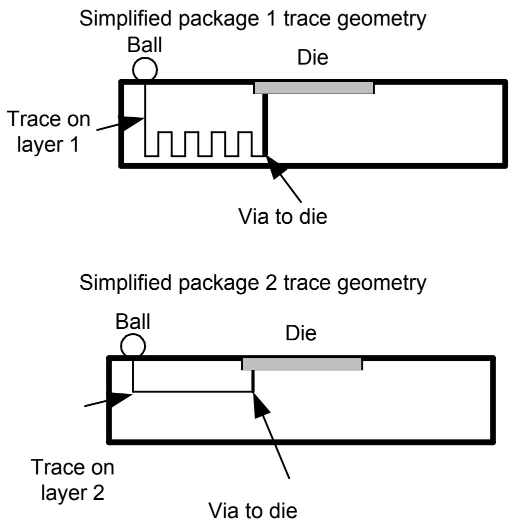


Figure 10. Sample package trace geometries used for correlation to the impedance profiles.

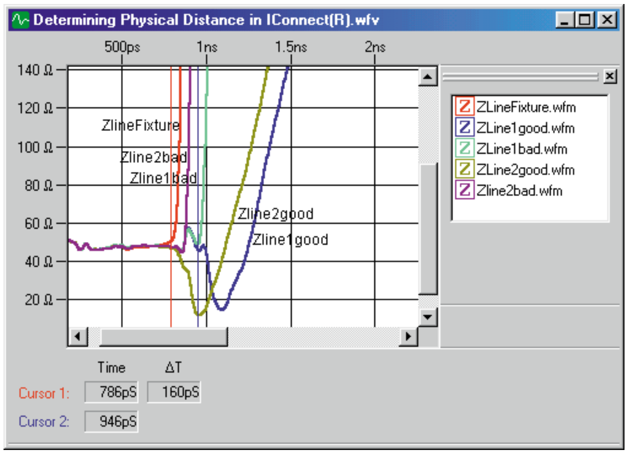
The TDR waveform comparative analysis may also yield sufficiently accurate results. However, pinpointing the exact location of the failure may prove to be difficult. For example, see figure 6.

Additional considerations for package failure analysis

The true impedance profile is very powerful because it opens up other interesting venues for FA on electronic packages. For example, because the true impedance profile represents an exact signature of the DUT, one can now analyze the package impedance profile and quite easily correlate it to the physical layers in the BGA package, which can be observed in the package layout or drawing.

Consider the following two package samples with the following simplified trace layouts in figure 10. The two packages are quite similar, except that the trace leading to the via connecting the package trace to the die is significantly longer for package 1. Both of these packages were analyzed with a TDR instrument and an impedance profile in IConnect® software. In both cases a good package sample and a sample with a failure of the connection between the package trace and the die has been analyzed.

The impedance profile enables a simple correlation to the package geometry (fig. 10). In package 1, the known good waveform (Zline1good.wfm) shows a segment with inductive behavior (estimated to be about 2nH in inductance), correlating to the long package trace, then a short segment correlating to the via, and then a segment correlating to the input capacitance of the die. When the connection to the die is broken, the corresponding waveform (Zline1bad.wfm) still shows the long trace in the package, but does not go into the capacitance of the die (estimated to be 800fF). Finally, the shorter second package trace correlates to the shorter section in the impedance profile waveform (Zline2good.wfm), whereas for the failed trace in package 2, the impedance profile goes up to high impedance at a much earlier point. The estimates for the inductance of the trace and input capacitance of the die match the expected numbers well, which provides further confirmation for the accuracy



	Time	ΔT
Cursor 1:	786pS	160pS
Cursor 2:	946pS	

Figure 11. Layer correlation and distance analysis in IConnect based on the impedance profiles of two packages with similar layouts.

of the analysis of the failure type and location.

Once the correlation from the physical package structure to the impedance profile waveform has been determined, the location of the fault in the package can be found easily.

In addition, since the overall physical length of the package trace can be quickly found from the package layout, and the impedance profile provides exact information about the electrical length of the package trace, this correspondence can provide a reasonably good estimate of the physical location of the failure. For example, if the package layout software gives a reading for the overall package trace length of l_{total} meters, and the true impedance profile shows that the package length is $t_{d\ total}$ seconds, then the average relative velocity of propagation through the package can be estimated as

$$V_{prop\ average} = \frac{l_{total}}{t_{d\ total}} \cdot \frac{1}{V_C} \qquad (2)$$

where V_C is the speed of light. For example, the difference between the length of the traces in package 1 and package 2 is 45 ps (90 ps round trip). Based on the layout file data, the corresponding physical length is 10 mm, which provides an estimated relative velocity of propagation of 4.5 ps/mm, or 0.74 the speed of light. Corresponding effective dielectric constant will be $\varepsilon_r = (1 / 0.74)^2 = 1.8$.

In addition, if a correlation between an electrical position in seconds to the physical position in meters needs to be estimated, it can be done using the following equation:

$$l = t_d \cdot \frac{l_{total}}{t_{d\ total}} \qquad (3)$$

Using equation (3), one can estimate the relative position of the failure within a layer, if it is suspected that the failure actually occurred within a layer.

Clearly, equations (2) and (3) are only estimates. The propagation velocity will vary through the different layers in the package. To get a more accurate value for the propagation velocity one needs to do extensive characterization of the package substrate material, as well as other substrate characteristics. Such characterization is very time consuming and requires that special test structures be laid out on the material under test ([7] and [8]). Because of such complexity, the exact data about the velocity of propagation through the separate package layers are rarely available to a failure analyst. A much easier approach is to correlate the layers in the package to the segments in the true impedance profile and use equation (2) to estimate the propagation velocity in each layer. However, sufficient resolution of the TDR instrument is required to resolve the layers, which can be on the order of 10 ps or less.

An attractive approach for a failure analyst could be to model the package under test, and then attempt to predict the TDR waveform of the package trace via SPICE or full-wave circuit simulations. The problem with this approach is, again, that the properties of the package material must be known with a reasonably high level of accuracy in order to ensure that the simulation predicts the TDR waveform correctly, unless the package model has been directly extracted from TDR measurement.

Summary and Conclusions

In this paper, we discussed TDR measurement technology as it applies to the failure analysis of electronic packaging. We analyzed the impedance deconvolution algorithm, and demonstrated the advantages that the true impedance profile (resulting from applying this algorithm to the TDR data), provides for a package failure analyst over a simple TDR data set, for both signature and comparative package failure analysis. Additional analyses were presented, which can be performed on the true impedance profile, and that can further simplify the location of the failures in electronic packaging.

Acknowledgements

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