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Comparison Study of Time Domain Reflectometry (TDR) Measurement Methods for Detecting Wire Interconnect Related Open-Contact and Short-Contact Failures in Power Semiconductor

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Abstract

Open-contact and short-contact are 2 common failures that causing power semiconductor to have electrical malfunctioned. One of the reasons of these failures relate to defective in the wire interconnect. Time domain reflectometry (TDR) is a common method widely used to detect failures in semiconductor devices. This study focused on comparing 3 different TDR measurement methods in detecting wire related open and short failure for power semiconductor, namely Single-Ended method, Single-Pin Grounded method and All-Pin Grounded method. A special custom-made jig is used during the measurements to ensure all the methods are measured under the same conditions. This study shows that all the 3 TDR measurement methods are able to detect wire related open and short failures in power semiconductor. The Single-Pin grounded method is the preferred method because it is easy in term of setup and having the good capability in detecting both open and short failures. Furthermore, the study also shows that the TDR is able to detect the location of open and short failures that is not able to achieve by using the conventional electrical testing method.

Keywords: Time domain reflectometry, TDR, Open-contact, Short-contact, Measurement method

Introduction

Power semiconductors are major components applied in modern electronic applications. They are widely used in automotive, consumer electronics, military and aerospace and industrial segments [1,2]. Examples of common power semiconductors are power diode, thyristor, power MOSFET and IGBT [1-5].

One of the important interconnecting methods for power semiconductor is by using wire bonding [6,7]. The purpose of wire interconnection is to provide electrical connectivity between the semiconductor IC and external leads. Two common electrical failures related to the wire interconnection are open-contact and short-contact. The open-contact failure can be due to non-stick on lead (NSOL), non-stick on pad (NSOP) or broken wire [8,9]. The short-contact failure can be due to sagging wire, distorted wire or wire sweep [10-12], that lead to the wire contacts with either the adjacent wire or lead post. Those devices with open or short-contact failures including those failing electrical test are sorting out from the good devices at the final electrical testing of power semiconductor [13-15].

Time domain reflectometry (TDR) is widely used in the electronics industry such as to detect failure in semiconductor components [16-19], characterizing the circuit board [20], measuring the C-V characteristics of semiconductor chip [21] or even detecting fatigue in the solder joint [22,23]. TDR is superior as compared with other non-destructive techniques such as scanning acoustic microscopy (SAM) and X-ray inspection [16,17] because on top of TDR is a non-destructive test; it is also capable of pointing out the type of failure (short, open, capacitive or inductive characteristics) based on the impedance mismatched. Furthermore, TDR is able to estimate the location where the failure happened. From the literature, the 3 common TDR measurement methods used are Single-Ended Method [24,25], Single-Pin Grounded Method [17,26] and All-Pin Grounded Method [27,28].

The objective of this study is to compare the 3 different TDR measurement methods in detecting wire related open and short failures in power semiconductor. The short failures to be investigated are wire-wire short and wire-lead short, while the open failures focus on wire breaks at different locations. The expectation of the study is to determine which TDR measurement methods is simple in term of measurement setup and yet still provide good capability in detecting wire related open and short failures. Furthermore, this study will also validate whether the TDR is able to detect the location of short and open along the wire that would not be able to achieve with conventional electrical testing method. In order to ensure all the 3 measurement methods is able to compare under the same conditions, a custom-made jig is fabricated and used during the whole study.

Materials and methods

Working principle of TDR

The working principle of TDR is based on wave propagation and transmission line theories [29,30]. **Figure 1** shows the basic construction of TDR. TDR consists of a high-speed oscilloscope and a step pulse generator. The step pulse generator generates fast pulses (typically in the picosecond range) and transmits them into a transmission path under study. These input pulses are termed incident pulse ($V_{incident}$). If there is impedance mismatched along this transmission path, reflective pulses ($V_{reflection}$) are generated and bounced back to the TDR. The high-speed sampler process both the incident and reflected pulses and show the results as a graphical signal on the screen of the oscilloscope.

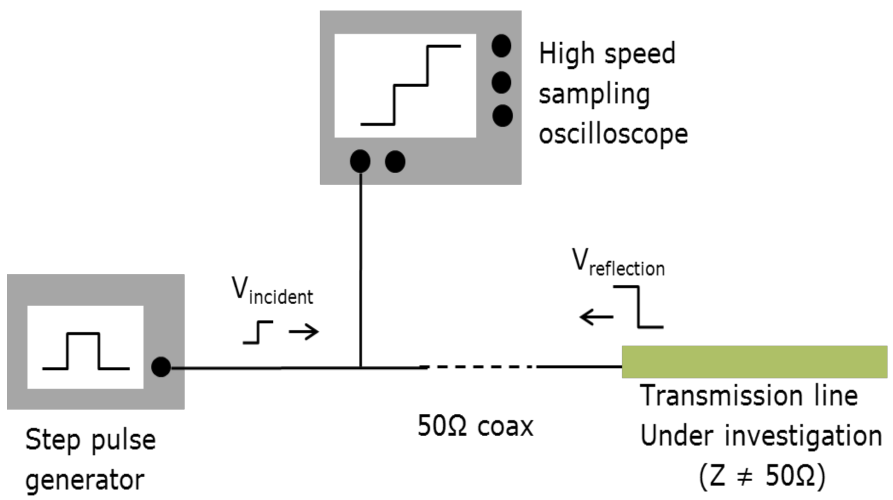


Figure 1 Typical setup of TDR.

The TDR signal is measured as reflection coefficient (ρ), which is the ratio of amplitude between the reflective and incident pulses as in Eq. (1) [31]:

$$\rho = \frac{V_{Reflection}}{V_{Incident}} \tag{1}$$

It is also commonly defined the reflection coefficient in term of load impedance (Z_O) and characteristic impedance (Z_L) as in Eq. (2) [31]:

$$\rho = \frac{Z_L - Z_O}{Z_L + Z_O} \tag{2}$$

The typical value of Z_O is 50 Ohm while Z_L is the impedance along the transmission path. **Figure 2** is showing the typical responses of the reflective coefficient curve when there is open-contact and short-contact. The reflection coefficient ranges between +1 and –1. In view of this, by looking at the characteristic of the TDR signal, one can determine whether the transmission path either is having open or short failure by looking at whether the response is a step up towards +1 or step down towards –1.

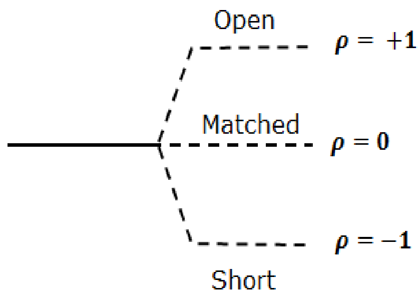


Figure 2 Response of TDR.

It is also possible to estimate the failure location by using Eq. (3) [30]:

$$d = \frac{T_d/2}{V_P} \quad (3)$$

where: d = distance.

Td = time delay obtained from the TDR curve. Since Td is the time for full cycle, there is a need to divide it by 2.

Vp = velocity of propagation.

Experimental setup

In this study, smart power semiconductor with 7 pins and packed it in the TO263 package were used as test samples. The device was bonded with 8 thin aluminium wires that having a wire diameter of 75 µm. The TDR used was a Tektronix TDS8200 with TDR module 80E04 up to 20 GHz bandwidth with approximately 23 pSec incident rise time.

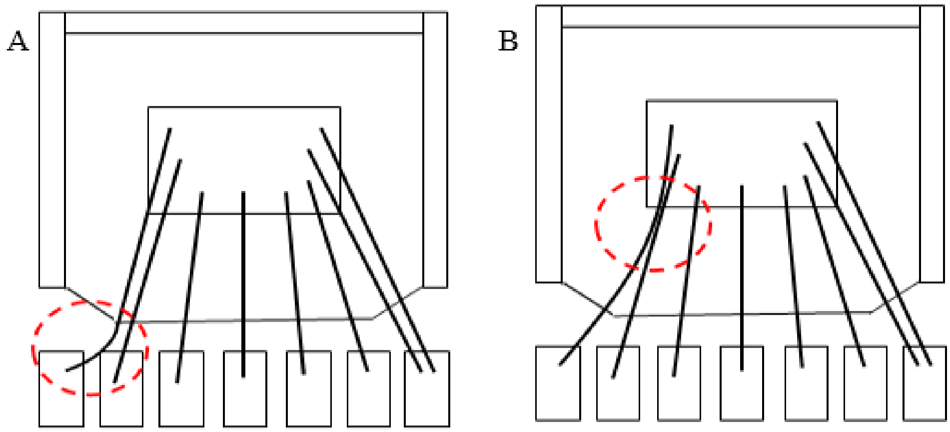
Sample groups

Total of 18 power semiconductors samples with wire related failures were purposely fabricated for this study. These samples were divided into 6 different experiment groups, where each group consists of 3 test samples as summarized in **Table 1**. The first 2 groups, S1 and S2, were the short-contact samples. The former group consists of wire-lead short samples, and the latter group consists of wire-wire short samples. The difference is illustrated in **Figure 3** respectively.

On the other hand, group O1 to O4 were the groups with open-contact failure samples. **Figure 4** shows the failure location for each group. Group O1 consists of samples with open-contact at position 1 (Pin1, Lead side); Group O2 at position 2 (Pin1, Chip side); Group O3 at position 3 (Pin2, Chip side) and lastly Group O4 at position 4 (Pin2, Lead side). After the wire defects were created, all the samples were going through the normal TO263 semiconductor packaging processes. Samples were also being electrically tested to compare with the results obtained by the TDR measurements.

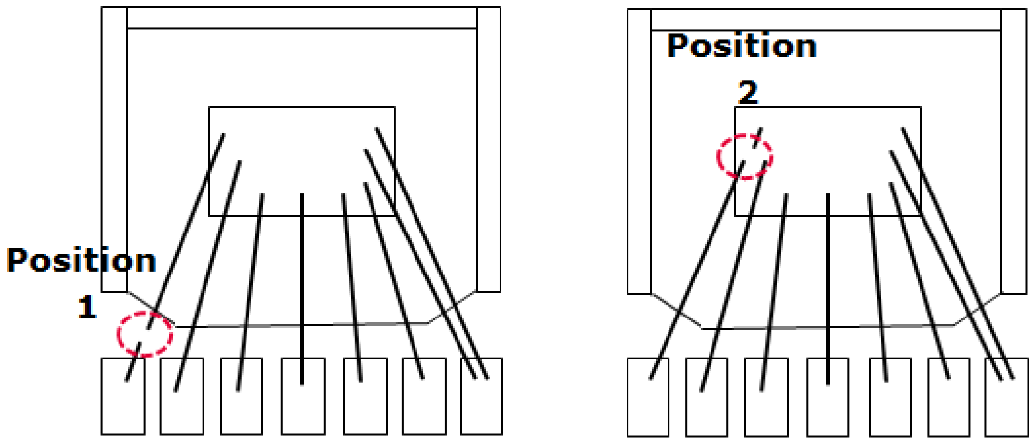
Table 1 Summary of all the sample groups.

Failure simulated	Sample group	Description of group	Purpose
Short	S1	Short between Wire-Lead	To test the capability of TDR in detecting short at different locations.
	S2	Short between Wire-Wire	
Open	O1	Open at Position 1 (Pin1, Lead side)	To test the capability of TDR in detecting open at different locations.
	O2	Open at Position 2 (Pin1, Chip side)	
	O3	Open at Position 3 (Pin2, Chip side)	
	O4	Open at Position 4 (Pin2, Lead side)	

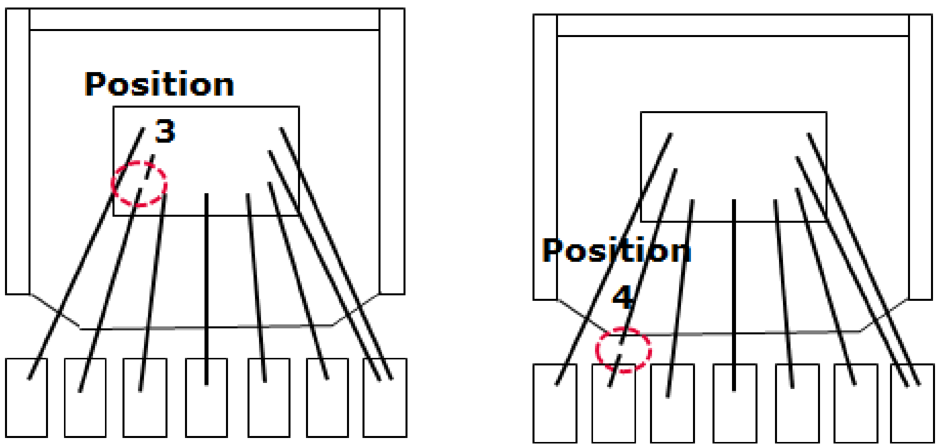


(a) Group S1: short between wire to lead. (b) Group S2: short between wire to wire.

Figure 3 Experimental groups with various short-contact failure samples.



(a) Group O1: open at Position 1 (Pin1, Lead). (b) Group O2: open at Position 2 **(**Pin1, Chip**)**.



(c) Group O3: open at Position 3 (Pin2, Chip). (d) Group O4: open at Position 4 (Pin2, Lead).

Figure 4 Experimental groups with various open-contact failure samples.

Custom-made jig

As the TDR measurement is very sensitive to the placement and pressure between the probe and the test sample, a custom-made test jig was designed for this experiment. This is to ensure all the data collected for all the experiments were under the similar conditions. The design of custom-made jig is shown in **Figure 5**. The base of the jig was a ceramic board where portion of it wrapped with copper tape. A small slit was made at the centre of copper tape with an opening slightly larger than the width of the component's lead. The slit shall not totally cut through the whole width of the copper tape in order to ensure the right and left sides of the copper tape were still connected.

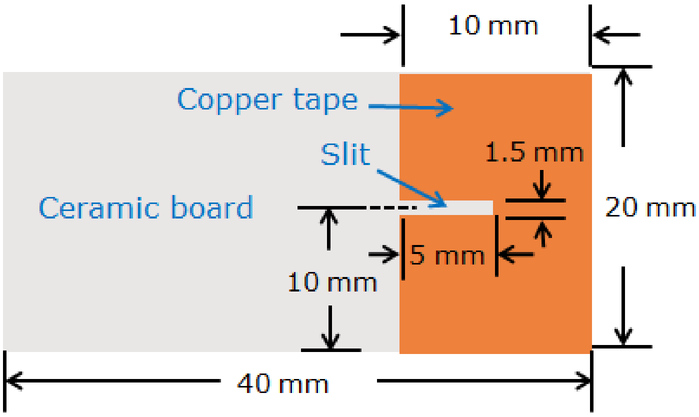


Figure 5 Design of custom-made jig.

Measurement methods

The 3 TDR measurement methods by using the custom-made jig are being further described in the below section.

Single-Ended method

In order to perform measurement using this method, placed the sample on the jig with both the bottom heatsink and pins sitting at the area without copper tape. For the measurement, probed the pin under investigation with the TDR probe without grounding at the other pins. The measurement setup is as shown in **Figure 6**.

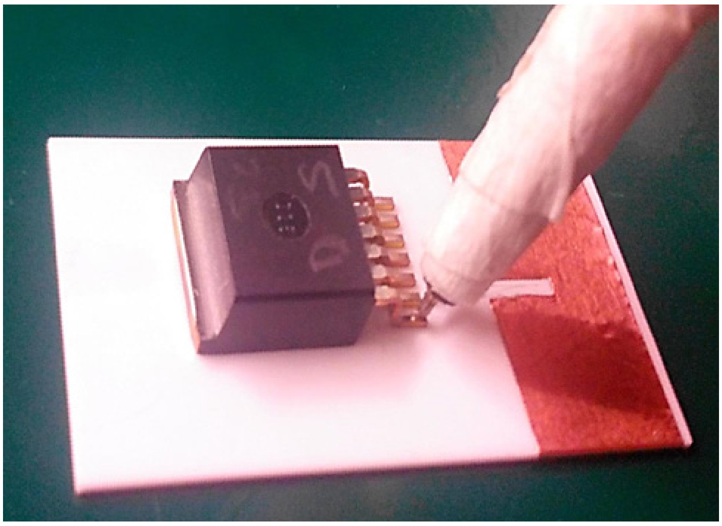


Figure 6 Setup for the Single-Ended method.

Single-Pin Grounded method

Figure 7 shows the setup for the Single-Pin Grounded method. Placed both the back heatsink and pins of the sample on the jig in the area without copper tape. However, on top of probing at the pin under investigation, grounded the adjacent pin while all other pins were left open during the measurement.

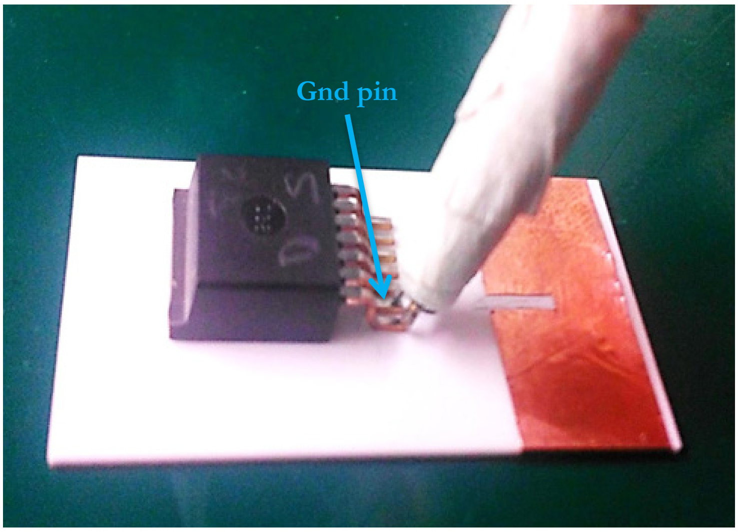


Figure 7 Setup for the Single-Pin Grounded method.

All-Pin Grounded method

To perform this measurement method, placed the sample on the jig with the back heatsink sitting on the portion without the copper tape. However, the pin under investigation was now being placed at the slit while the rest of the pins were sitting on the copper tape as shown in **Figure 8**. With this, the pin under investigation was totally being isolated from the rest of the pins. Probed the pin under investigation with the TDR probe and grounded the adjacent pin. Due to the adjacent pin was touching the copper tape together with all other pins (except the pin under investigation); the copper tape will provide the electrical connectivity to ground all these pins as well. **Figure 9** is showing the complete setup using this measurement method.

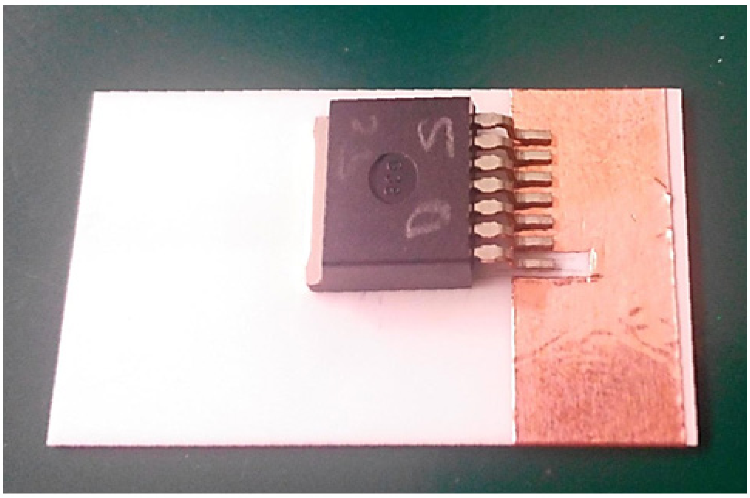


Figure 8 Pin under investigation placed at the slit while the rest of the pins are in contact with copper tape.

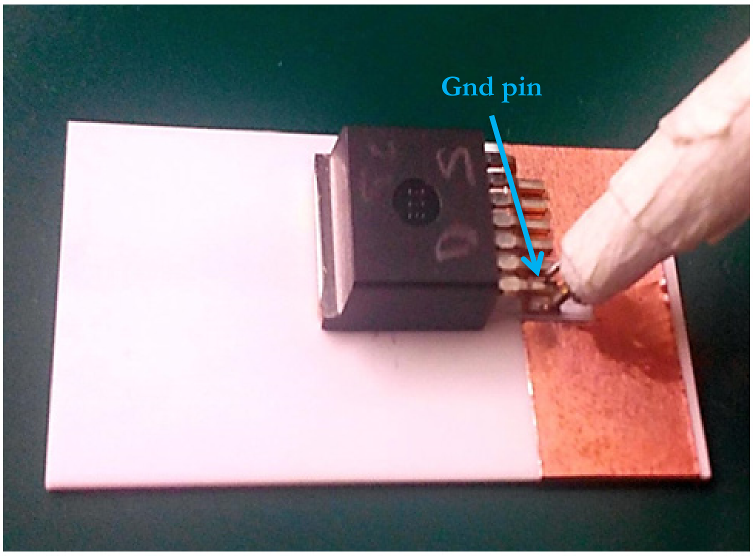


Figure 9 Setup for the All-Pin Grounded method.

Results and discussion

Results

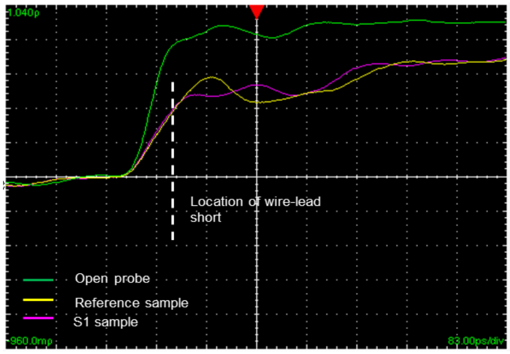
Table 2 shows the summary of results from the electrical testing for different sample groups. Both the Group S1 and Group S2 were only showing as Bin5 short-contact failure. Similarly, the samples with open-contact were only showing as Bin5 open-contact failure for Group O1 to O4. The electrical test was not able to show the location for short and open failures.

Table 2 Summary of the results from electrical test.

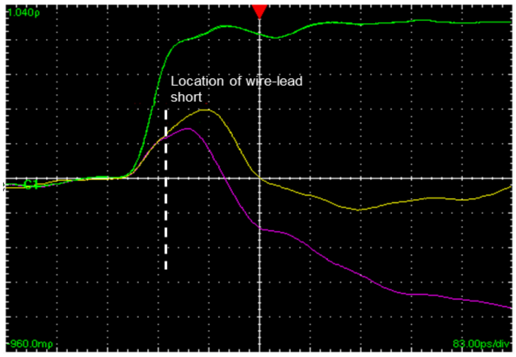
Failure simulated	Sample group	Failure location	Electrical bin	Electrical bin
Short	S1	Wire-Lead	Bin5 short	3/3
	S2	Wire-Wire	Bin5 short	3/3
Open	O1	Position 1	Bin5 open	3/3
	O2	Position 2	Bin5 open	3/3
	O3	Position 3	Bin5 open	3/3
	O4	Position 4	Bin5 open	3/3

Figure 10 shows the results for Group S1 (wire-lead short), while the results for Group S2 (wire-wire short) as shown in **Figure 11**. These results are measured using 3 different TDR measurement methods: Single-Ended, Single-Pin Grounded and All-Pin Grounded. The Y-axis was the reflection coefficient with a scale of 8 mρ/div. The X-axis was the time domain with the scale set at 83 pSec/div. The scales are identical across all the measurement. Since all the 3 samples from each group produces similar TDR characteristic, only a TDR curves from one of the samples were shown in this paper.

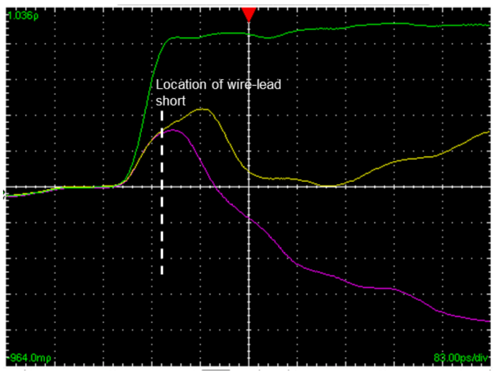
By comparing the reference curve (yellow) and measurement curve (purple), the TDR measurement methods were able to detect both the wire-lead and wire-wire short failures. However, the Single-Pin Grounded and All-Pin Grounded methods demonstrated a better detectability on the short failure as compared to Single-Ended method. One can observes easily from the TDR curve where after the short failure location, the measurement curve shifted to lower reflection coefficient to indicate the detection of short failure on that sample.



(a) Single-Ended method.

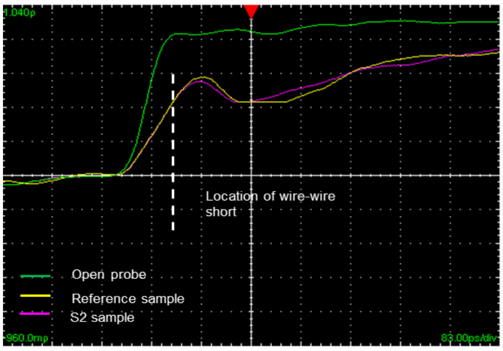


(b) Single-Pin Grounded method.

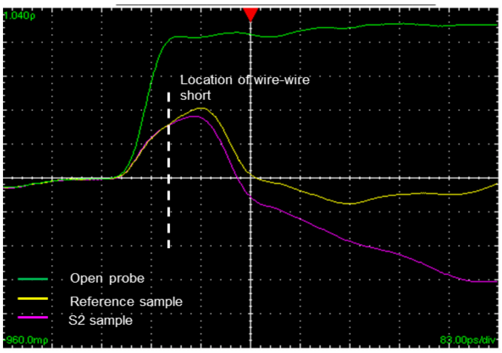


(c) All-Pin Grounded method.

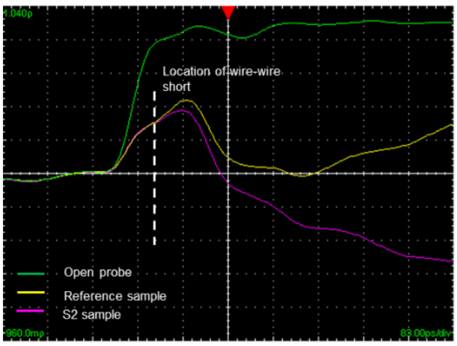
Figure 10 TDR responds for wire-lead short.



(a) Single-Ended method



(b) Single-Pin Grounded method

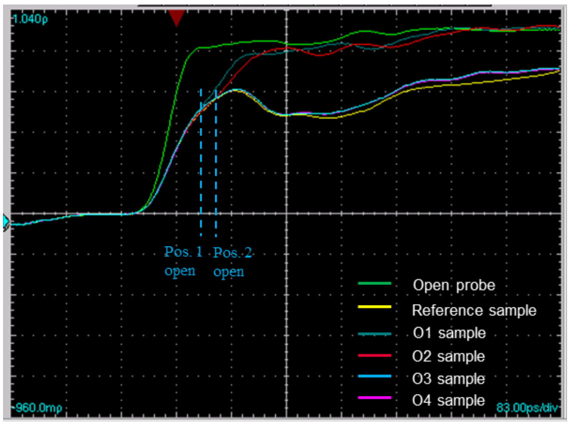


(C) All-Pin Grounded method

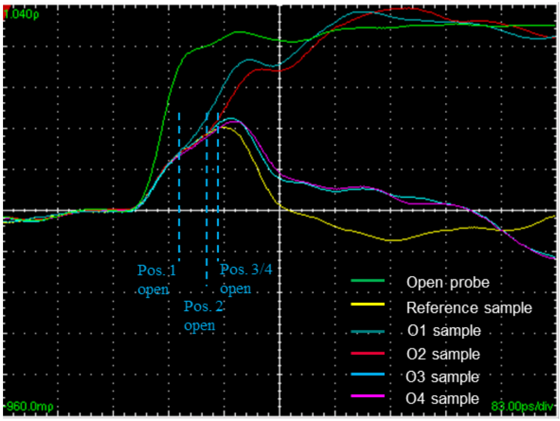
Figure 11 TDR responds for wire-wire short.

Figure 12 shows the TDR responses from the open failure experiments. Three methods proposed in this study able to detect open failure for Position 1 (Pin1, Lead) and Position 2 (Pin1, Chip). Both the Single-Pin Grounded and All-Pin Grounded methods were able to detect additional open-contact, but unfortunately unable differentiate whether the open-contact was at Position 3 (Pin2, Chip) or Position 4 (Pin2, Lead).

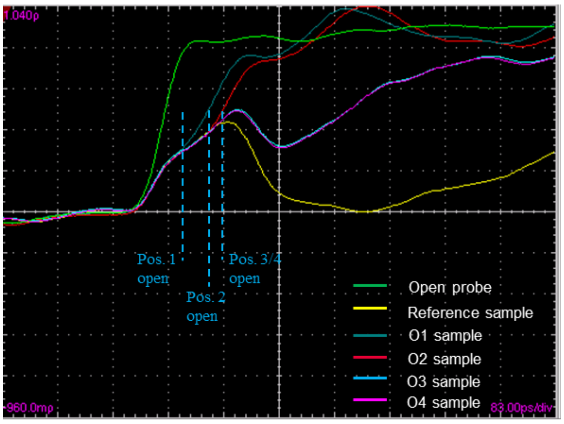
The TDR measurements were also showing good results for all the measurement methods when come to determine the failure location. The TDR curves obtained from Single-Pin Grounded method are used as an example to explain the results. Comparing between **Figures 10(a)** and **11(a)**, where both with short failures but happened at different locations, the TDR responses started to deviate from the reference curve at different time (white dotted line). For **Figure 10(b)** with wire-lead short, the TDR response started to deviate at 43.834 nSec. For **Figure 11(b)** with wire-wire short, the TDR response started to deviate at 43.859nSec. The same goes for open failures. Based on **Figure 12(b)**, the TDR response started to deviate at 43.837 nSec for Position 1, 43.887 nSec for Position 2 and 43.899 nSec for Position 3 or Position 4 respectively (blue dotted lines). The results are summarized in **Table 3**.



(a) Single-Ended method.



(b) Single-Pin Grounded method.



(C) All-Pin Grounded method.

Figure 12 TDR responds for open failure.

Table 3 Failure location detected by TDR using Single-Pin Grounded method.

Failure simulated	Sample group	Failure location	TDR time (nSec)
Short	S1	Wire-Lead	43.834
	S2	Wire-Wire	43.859
Open	O1	Position 1	43.837
	O2	Position 2	43.887
	O3	Position 3	43.899
	O4	Position 4	43.899

Discussion

In this section, the discussion is on why the TDR curves for different measurement methods behave in such a way during detecting the open and short failures. The discussion also discuss easiness in term of the setup and how good the TDR in detecting the open/short failures and failure locations. The comparisons between the electrical testing and all the TDR measurement methods are summarized in **Table 4**.

Table 4 Comparison on all the measurement methods.

Electrical test			TDR			
Failure type	**Electrical bin**	**Detectable failure location**	**Measurement method**	**Detectable failure location**	**The shift of the TDR curve**	**Setup**
Short	Bin5 (short-contact)	Not able to differentiate short location at wire-wire and wire-lead	Single-Ended	Wire-wire, Wire-lead	Minor	Easy
			Single-Pin Grounded	Wire-wire, Wire-lead	Obvious	Easy
			All-Pin Grounded	Wire-wire, Wire-lead	Obvious	Medium
Open	Bin6 (open-contact)	Not able to differentiate open location at Position 1 to Po sition4	Single-Ended	Pos ition1, Po sition2	Minor	Easy
			Single-Pin Grounded	Pos ition1, Pos ition2, Pos ition3/4	Obvious	Easy
			All-Pin Grounded	Pos ition1, Pos ition2, Pos ition3/4	Obvious	Medium

TDR response for wire short failure

When detecting the short failure using the Single-Ended method, due to there is no grounding, it acts like a transmission line with an open-contact at the end of the transmission path. At the location with wire having short-contact, lower impedance is expected. In view of this, the TDR reflection coefficient steps down at the short location before continues towards the +1 as there is open-contact at the far end (**Figures 10**(**a**) and **11**(**a**)). As for both the Single-Pin Grounded and All-Pin Grounded methods, they act like the normal transmission line with grounding at the end of the transmission path (**Figures 10**(**b**), **10**(**c**), **11**(**b**) and **11**(**c**)).

TDR response for wire open failure

When detecting the open failure, all the methods are going through the same transmission path at Position 1 and Position 2. Due to this, if there is an open-contact at Position 1 or Position 2, the reflection coefficient curve will step up and continue to +1 for all the methods.

For the Single-Ended method (**Figure 12**(**a**)), when there is open at Position 3 and Position 4, the open contact is at the far end of transmission line. The TDR signals transmit into the semiconductor chip and have great signal energy lost before can reach the location with open contact at the other end. In view of this, there is no significant shifts of the curve if open contact happened on these 2 positions.

For the Single-Pin Grounded method (**Figure 12**(**b**)), when there is an open at Position 3 or Position 4, it loses the ground contact. It behaves like an open-ended transmission line and thus the reflection coefficient curve is moving towards the +1.

For the All-Pin Grounded method (**Figure 12**(**c**)), the reflection coefficient curve is not moving towards +1 at the open location at Position 3/4. It is moving towards –1 since other leads providing the grounding effect.

TDR detectability and easiness of setup

From the results in Section 4, both the Single-Pin Grounded and All-Pin Grounded methods are more superior comparing to the Single-Ended method. For the short failure conditions, both the grounding methods are providing better visibility on the curve shift. In the open conditions, both the grounding methods can detect up to Position /Position 4. Although both the grounding methods are not able to differentiate Position 3 or Position 4, this is already good enough to serve as a pre-warning that there is an open connection at the adjacent lead. By performing subsequent measurement at the adjacent lead, the exact open location at Position 3 or Position 4 can be easily determined.

In term of setup for the measurements, both the Single-Ended and Single-Pin Grounded methods are easy to setup. Single-Ended method just need a single probe; while the Single-Pin Grounded method needs only a single probe and ground the adjacent lead. For the All-Pin Grounded method, additional precaution needs to ensure all the leads grounded properly. It also needs to ensure the lead under investigation is not contact with copper tape that can cause shorting to the ground.

Failure location

It is also interesting to find that the TDR is able to detect the location of open and short failures that not able to achieve with the conventional electrical testing method. Comparing **Figures 10**(**b**) and **11**(**b**), the curve of the wire-lead shift from the reference curve much earlier and there is a time delay (Td) of 25 pSec between the wire-lead and wire-wire short. This is in-line with the failure location as wire-wire short is located further from the lead that being probed.

The same goes for open failures. In **Figure 12**(**b**), there is a time delay (Td) of 50 pSec between open at the lead (Position 1) and chip (Position 2) of Pin1. Since the Td is already known, and the distance (d) of the wire open failure from lead to chip able to be measured, it is possible to estimate the propagation velocity (Vp) of aluminium wire in the plastic moulded package by using Eq. (3). By knowing the propagation velocity, in future, the distance of any failure location along the wire is able to calculation easily again and with the Td value from the TDR. With modern TDR system that is having higher pulse rate at 50 GHz, the detectability of the failure location can be further enhanced [24].

Conclusions

In this paper, comparison on all the 3 different TDR measurement methods in detecting open and short due to wire failure on Power semiconductor had been studied. The TDR measurement methods are Single-Ended method, Single-Pin Grounded method and All-Pin Grounded method. A custom-made jig that is easy to fabricate is used throughout the whole study and can ensure all the measurements are performed under the same conditions.

From the study, all the 3 TDR measurement methods are able to detect open or short due to wire related failure in Power semiconductor. Single-Pin Grounded method is the preferred TDR measurement method since it is not only easy in term of measurement setup, but also provides good detectability of the wire related open and short failure.

The study also shows that TDR is able to detect open at short at different locations that cannot achieve with conventional electrical testing. Single-Pin Grounded method is comparable with All-Pin Grounded method and better than Single-Ended method in detecting the failure locations.

Overall, the study shows that Single-Pin Grounded method is the best among the 3 TDR measurement methods since it is easy to setup, good open and short failure detectability and able to detect the failure location.

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