Transient Solder Separation of BGA Solder Joint During Second Reflow Cycle

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Abstract

As the demand for higher routing density and transfer speed increases, Via-In-Pad Plated Over (VIPPO) has become more common on high-end telecommunications products. The interactions of VIPPO with other features used on a PCB such as the traditional dog-bone pad design could induce solder joints to separate during the second and thereafter reflows. The failure has been successfully reproduced, and the typical failure signature of a joint separation has been summarized [1].

To better understand the solder separation mechanism, this study focuses on designing a test vehicle to address the following three perspectives: PCB material properties, specifically the Z-direction or out-of-plane Coefficient of Thermal Expansion (CTE); PCB thickness and back drill depth; and quantification of the driving force magnitude beyond which the separation is due to occur.

The test vehicle is designed such that each VIPPO pad is surrounded by dog-bone via pads and each of the VIPPO joints has independent daisy chain for in-situ monitoring during the second reflow cycle.

There are four different pad designs: all VIPPO design; VIPPO and dog-bone mixed pad design; VIPPO and skip via mixed pad design; and back-drilled VIPPO mixed pad design. The all VIPPO design is the baseline benchmark. The VIPPO and dog-bone mixed pad design is expected to be the worst case scenario. The VIPPO and skip via mixed pad design together with the VIPPO and back-drilled VIPPO mixed design areincluded to narrow the magnitude of inherent build-in stress induced by the CTE mismatch which causes the VIPPO joints to separate during the second reflow.

The test vehicles are fabricated with two different PCB materials. Material A is a traditional high-end PCB material with high Z-direction (out-of-plane) CTE; while Material B has approximately one third of the Z-direction CTE of Material A.

A Design of Experiment (DoE) with two PCB materials (Material A and Material B) and two PCB thicknesses (93mil and 125mil) has been performed. With the designed single-ball daisy chain test vehicle and installed thermocouples, the correlation between electrical continuity (daisy chain resistance) and solder joint temperature (thermocouple) can be derived.

A video was taken of two cross-sectioned samples during the second reflow cycle using a reflow simulator. The observation is consistent with the findings of the test vehicle (TV) for in-situ monitoring. The results also provide more accurate and broader information for the investigation on why, how, and when the solder separation occurred during the second reflow cycle.

Test Vehicle Design

The test vehicle is 4” x 5” in size with OSP surface finish. The board material and thickness are listed in the DoE matrix (Table 1). Three factors are considered in the DoE matrix: PCB material; PCB thickness; and the pad/via design.

Based on the findings of the previous study [1], the CTE mismatch between the PCB material and Cu inside of PCB is believed to be the primary driving force for the solder separation, particularly when the temperature is above the PCB’s Tg. To verify this, a PCB material (Material B) with a much higher Tg and much lower out-of-plane CTE, when compared to the benchmark material (Material A), has been selected to build the TVs. Based on datasheet, the Material B has a Tg at 270°C and CTE of 12 and 100 ppm/°C below and above Tg, respectively. Therefore, the TVs built with Material Bare expected to have less or no solder separation failures.

Table 1 DoE Matrix with Material Properties

Leg	PCB Material	Tg* (°C)	CTE** ppm/°C <Tg	CTE** ppm/°C >Tg	PCB Thickness (mil)	Reference Designator U1 All VIPPO	U2 VIPPO & Dog-bone	U3 VIPPO & Skip Via	U4 VIPPO w/ Back Drill	No. of Board	No of Part
1	Material A	185[1]	45	260	93	1	1	0	0	5	10
2	Material A				125	1	1	0	0	5	10
3	Material B	270[2]	12	100	93	1	1	0	0	5	10
4	Material B				125	1	1	0	0	5	10
									Subtotal	20	40

* [1]by DSC method.[2]by TMA method
** IPC TM-650 2.4.24. CTE of Cu is 16.7 ppm/°C.

Thermal expansion depends proportionally on the material CTE and the linear length of the material, so the two PCB thicknesses are included in the DoE as the second factor, which are 93mils and 125mils. The intent is to prove that the CTE mismatch impact on solder separation can be reduced, as the PCB thickness gets thinner. In other words, the 93mil thickness TVis expected to have less solder separation than the TV with 125mil thick PCB, since the magnitude of thermal expansion for the same material is reduced due to the decrease of linear length of thermal expansion.

For the third factor, there are four different pad/via designs in the DoE. The all VIPPO design at U1 is the benchmark, which is not expectedto have any solder separation failure. Due to the Cu barrel underneath the pad, the VIPPO design is expected to be stiffer than the dog-bone via design. Therefore, the VIPPO and Dog-bone mixed design at U2 is expected to have some solder separation failure. The VIPPO & Skip Via design at U3 and VIPPO & Back-drill design at U4 are prepared for the Phase III study, which is pending on the results of Phase II. The Phase III study will proceed, if the higher Tg lower CTE PCB material and PCB thickness are confirmed to be controllable factors and valid mitigation tools for solder separation defect.

Daisy Chain Design
The four key solder separation questions to be answered through this study are

1. Is the solder separation initiated in solid state or liquid state? In other words, is it before or after solder melting temperature of the joint?
2. Is the solder separation location-specific, such as more separation happening at component corners or more in the center?
3. Once the solder joint separates, does it regain electrical continuity? How much does the resistance value change?
4. If it reconnected electrically, is the IMC (intermetallic compound) reformed and exhibits similar long-term reliability as it was prior to the solder separation?

In order to answer these questions, a unique daisy chain design with only one VIPPO joint per chain was incorporated (Figure 1). The VIPPO joint was surrounded by dog-bone via pads, which has a CTE mismatch of 16 versus 260 ppm/°C with Material A at temperature above Tg.

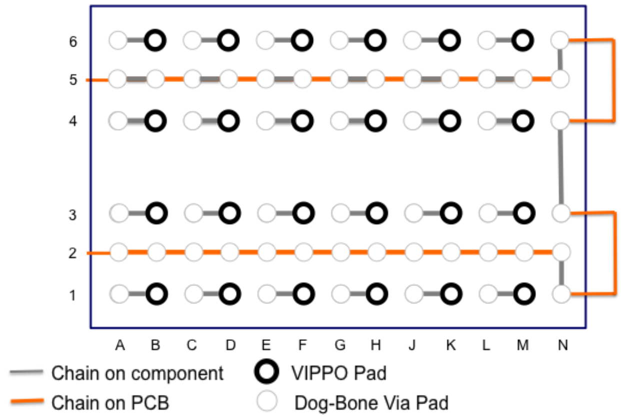


Figure 1 Daisy chain configuration at the VIPPO and dog-bone pad mixed design site, U2

There are a total of 25 chains at U2 location, which has the VIPPO and dog-bone via mixed design. Twenty-four chains are single VIPPO and dog-bone via pair. With the expectation of no solder separation failures, the rest of the thirty dog-bone via pads are all chained together in the 25th chain.

The 26th chain is for the all VIPPO site at U1 location, which is not expected to have any solder separation failure. Two thermocouples were used to monitor the temperature of the component and the board, which are the 27th and 28th channel.

Experimental Setup

The test vehicles were assembled on a production SMT line. Then, they were reflowed again using a production rework station. Twenty-five daisy chains and two type-K thermocouples were wired to a data logger for real time data monitoring and recording.

Figure 2 Experimental setup for the second reflow process

Separated Percentage Analysis

All twenty boards in the DoE matrix were reworked and analyzed. There were a few boards that required further analysis for the validity of the data. The results have been verified and shown in Table 2.

For the 125mil Material A, 84% of the solder joints with VIPPO and dog-bone mixed via design (U2) separated during the second reflow cycle. As expected, the 93mil PCB thickness with the same Material A had only 58% separated joints. It proves that the impact of CTE mismatch between Cu (VIPPO design) and PCB material (dog-bone via design) is less for the thinner PCB.

Table 2 Percentage of separated solder joints

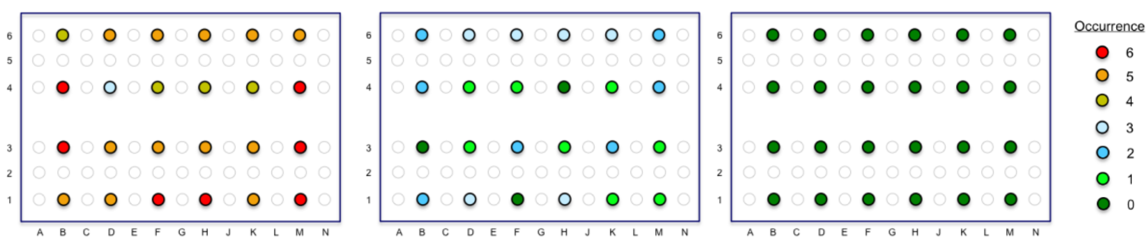
	Material A									Material B	
	125MIL						93mil			125MIL	
	TV1	TV2	TV3	TV4	TV5	TV6	TV1	TV2	TV3	TV1	TV2
Total Mixed Design	23	24	24	24	24	24	23	24	22	23	24
Separated (>100 Ohm)	19	19	18	23	19	22	15	14	11	23	24
% of Separated	83%	79%	75%	96%	79%	92%	65%	58%	50%	100%	100%
Overall Open %	84%						58%			0%	

None of the solder joints with Material B exhibited solder separation. The two boards verified are included in Table 2 as the representative boards. Material B has a Tg at 270°C, which is higher than the SAC305 liquidus temperature of 217°C. Therefore, the CTE was maintained at 12 ppm/°C, which is of the same magnitude as the Cu, around 17 ppm/°C. With no solder separation on Material B, it proves that the CTE mismatch between the Cu and PCB material is the key driving force which causes solder separation.

Though the percentage of separation exhibits a trend, it also reveals there is still a likelihood that the solder joint does not separate definitively with the mixed design. There are likely other minor factors that may contribute to the separation phenomenon that have not yet been discovered.

Separated Location Analysis

The location analysis depicting the frequency of separated solder joints are shown in Figure 3. Please note that the total number of boards are different. As shown in Table 2, there are 6 boards for 125mil Material A, 3 boards for 93mil Material A, and 2 boards for 125mil Material B.



Material A, 125mil, 6 boards   Material A, 93mil, 3 boards   Material B, 125mil, 2 boards

Figure 3Frequency of Separated Solder Joint Location Analysis

The pin mapping illustrating the frequency of separation was to determine if there is any significant failing trends on corner versus edge or inner pins. For the 125mil Material A boards, all 7 pins with 100% failing rate(6 out of 6) were all edge pins. A similar trend occurs with the 93mil Material A boards: all 6 pins with 100% failing rate (3 out of 3) wereall edge pins. However, corner pins fail less frequently in both thicknesses. This may be an indication that the CTE mismatch (between VIPPO and dog-bone pad design) inducing the local stress (or warpage) is dominating the thermal stress inducing the global warpage during the reflow cycle. In other words, the typical thermal Moiré warpage measurement may not serve as an effective control gate for alerting of solder separation.

Timing of Solder Separation

To fully understand the failure mechanism of solder separation, it is important to understand that when the separation is initiated— is it in solid state or liquid state. In other words, is it the liquid solder pulling away from the substrate? Or, does the solder joint experiences a brittle crack along the IMC line? And, once separated, will it re-connect and re-form to maintain electrical continuity?

Since each daisy chain has only one VIPPO pad, the separation and reconnection temperature can be detected when the resistance value changes abruptly. A sample analysis using 125mil TV4, TV5, and TV6 is shown in Figure 4.Out of the 71 VIPPO joints on these three boards, 63 separated. All 63 separated VIPPO joints re-connected in a short period of time.

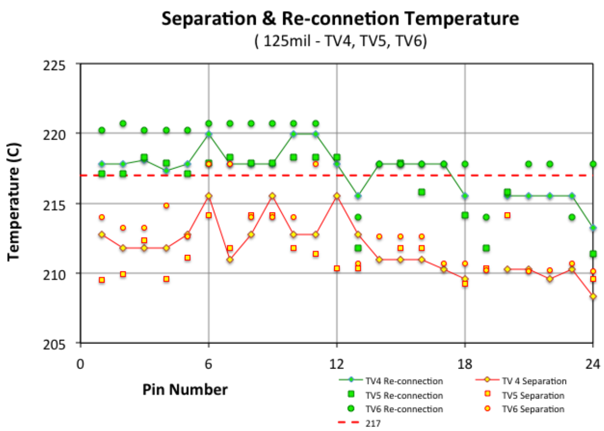


Figure 4 Separation and Re-Connection Temperature

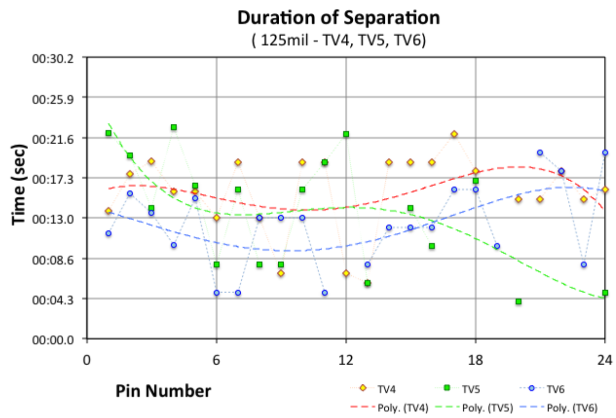


Figure 5 Duration of Separation

The majority of the VIPPO solder joint separation initiated between 210°C and 215°C and re-connected just above 217°C. It indicates the VIPPO solder joint separates from substrate in solid state, just before melting. Therefore, the failure mechanism is similar to the brittle crack along the IMC line.

Meanwhile, most of the VIPPO solder joints re-connected just after becoming molten solder. It may be due to the shape change driven by surface tension. Once the solder becomes liquid, the donut shape solder joint is reformed into a more spherical shape, which fills the separation gap and re-connects the electrical path.

The low re-connection temperature pins are in the same area as the non-separated pin area. For example, Pin 13, 16, 18, 19, 20, and 24 of TV5 are reconnected below 217°C. While on the same 4th and 6th row area, Pin 14, 17, 21, 22, and 23 did not separate during the 2nd reflow, which leaves only Pin 17 experiencing separation.

Duration of Separation
The duration of separation is defined as the time when the resistance value changes abruptly to a value that is less than 10 Ohms. As shown in Figure 5, the duration is in the range of 4 ~ 22 sec. The overall trend is between 9 ~ 18sec.

Changes in Resistance Value
Since all the separated solder joints regained continuity in a few seconds, is there any change of the resistance value before and after separation? Or is there any functionality loss due to solder separation?

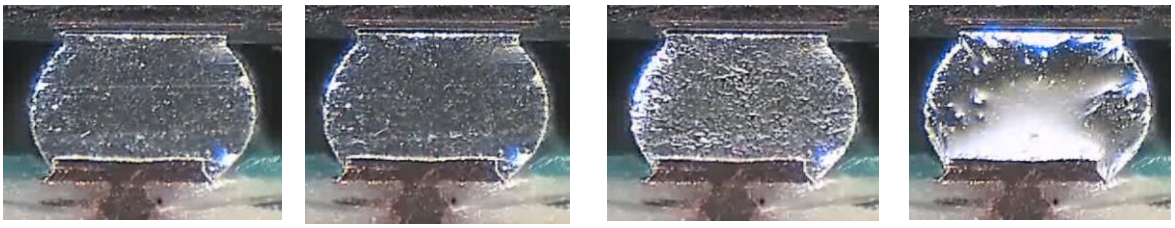
Most of the initial resistance are in the range of 1~3 ohms. After solder separation, re-connection and cool down to room temperature, the final resistance is in the same range of 1~3 ohms, with less than 5% change in value.

Therefore, the solder joint experiencing separation is likely passing all the subsequent electrical tests. Whether or not it willsurvive through the test with either additional imposed mechanical stress or thermal stress is an unknown at this time. This topic is related to the impact on long-term reliability. Both require product specific in-depth studies.

Failure Interface
To visualize the formation of solder separation, two samples were prepared and sent to a third party lab for a close-up high resolution video recording through the reflow cycle. The parts were polished to the quarter of the first row and placed in a convectionhot air reflow simulator chamber. The heating cycle was based on the production reflow profile.

In Figure 6, the four images are from the same VIPPO joint at different time of the reflow cycle. Comparing to the image on the very left (2:33), the VIPPO joint in the middle left at time code 2:35 (221°C) exhibits a separation between the solder ball and component substrate, when the solder is in solid state. The solder joint starts to melt at 2:42 (222°C).As the surface reflection pattern changes, the solder joint becomes fully liquidus at around 2:50 (224°C). The solder joint re-connects at 2:53 (225°C). The duration of separation is about 18seconds, which is consistent with the data from resistance value measurements in Figure 5.

Due to the differences of thermocouple installaion, the temperature reading of the reflow simulator is higher than the rework thermocouple readings by 7~10°C. After adjusting with liquidus temperature and synchronization with the data logger, the separation is initiated at 211~214°C and reconnects at 215~218°C. This is consistent with the resistance-temperature measurement from the data logger (Figure 4).



Before Separation (2:33) Separating (2:35) Start Melting (2:42) Become Liquidus (2:53)

Figure 6 Solder Joint Images from Reflow Simulator

By reviewing the video, it is observed that the dog-bone joints showed upward pushing as the reflow temperature increases, due to the excessive out-of-plane thermal expansion of the PCB material (as the red arrow indicates in Figure 7). The VIPPO joint separates before solder liquidus at the interface between solder and IMC of the component side; a small magnitude of pop-up of VIPPO joint at such an interface has been observed along with the sign of relief of upward pushing of the nearby dog-bone joint (Figure 8).

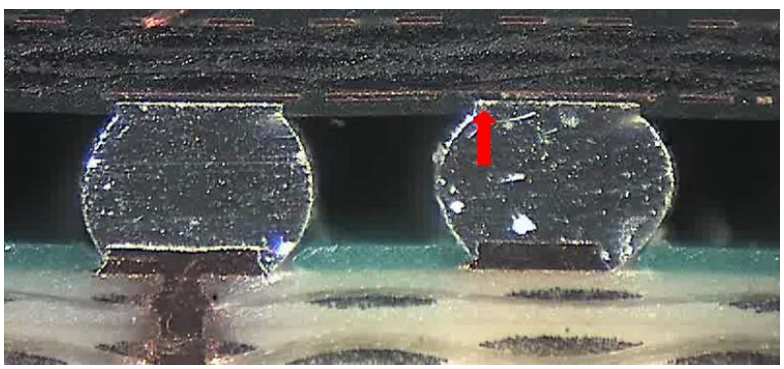


Figure 7 Solder joint image prior to separation, the dog-bone joint at the right side showed an upward pushing

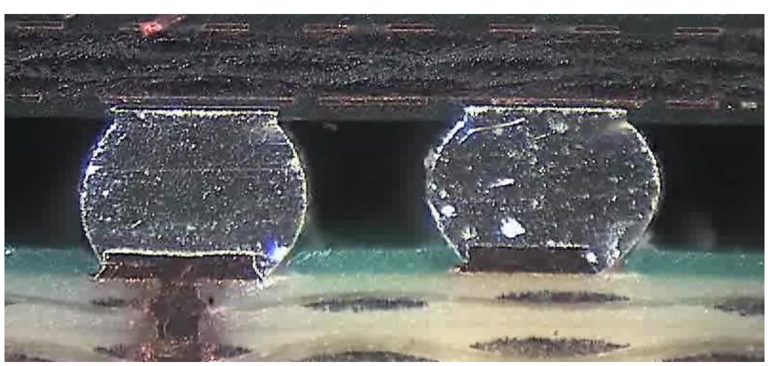


Figure 8 Solder joint image post separation, a pop up at the interface of VIPPO joint has been observed. Also, notice the relieve of the dog-bone joint on the right side

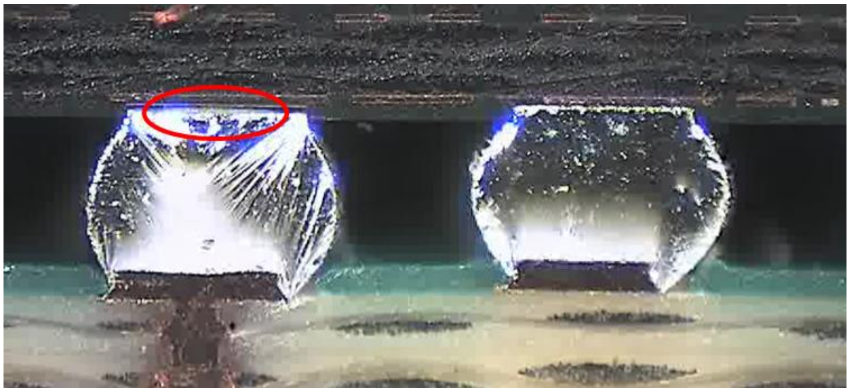


Figure 9. Molten solder of a separated VIPPO joint (left in the picture) retouching the top pad

Post-melting point, the molten solder forms a spherical shape due to the surface tension, and the solder sphere retouches the previously separated top pad (the red circle in Figure 9 shows the retouching). The phenomenon is consistent with the datalogger monitoring and confirms the previous FA findings [1]as shown in Figure 10.

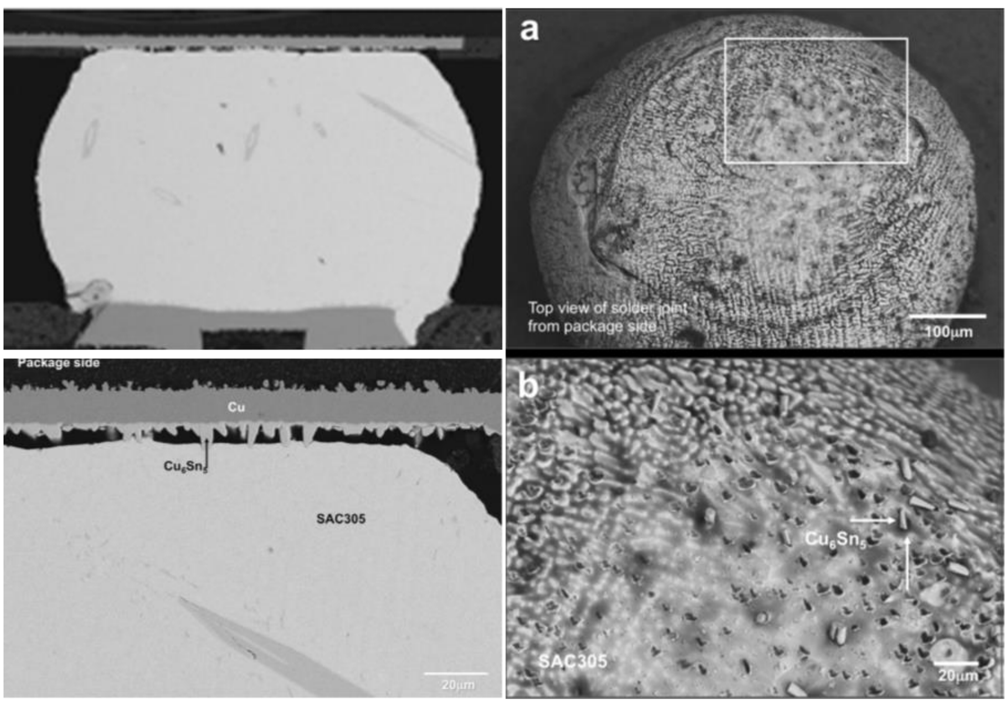


Figure 10. Cross section view of separation (left), and IMC pinching marks (right)

Conclusions

A thorough study of the mechanism for solder joint separation due to VIPPO and non VIPPO mixed designs has been conducted. The unique daisy chain design of the test vehicle enables independent in-situ monitoring of each VIPPO joint that is surrounded by non VIPPO joints. The results of such in-situ monitoring along with a close up video monitoring of the VIPPO joint during second reflow using a reflow simulator provide an in-depth understanding of the solder separation mechanism.

The key findings of this study are:

1. The primary driving force of solder joint separation is the out-of-plane thermal expansion of the PCB which includes two key factors: PCB material out-of-plane CTE and the thickness of PCB (or the depth of back drill);
2. The joint separation occurs before solder liquidus;
3. The separation happens at the interface between VIPPO solder and IMC at the component pad side;
4. The molten solder retouches the separated pad to regain electrical continuity but may or may not reform to be a good quality joint.

In summary, the electrical testing is not effective to identify the separated joints. The issue could be mitigated or even prevented initially ,if feasible, by either selecting PCB materials that have lower out-of-plane CTE and/or extremely high Tg or reducing the thermal expansion linear length such as the use of thinner PCBs.

Acknowledgement
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Reference

[1] Steven Perng, Weidong Xie, Tae-Kyu Lee, Cherif Guirguis, "Innovative BGA Defect Detection Method for Transient Discontinuity," SMTAi 2015, 2015