VIA-IN-PAD PLATED OVER (VIPPO) DESIGN CONSIDERATIONS FOR THE MITIGATION OF A UNIQUE SOLDER SEPARATION FAILURE MODE

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ABSTRACT

Increasing signal speeds (up to 28Gbps), board functional density and PCB layer count/thickness (up to 140 mils) are increasing the challenges associated with PCB design, especially with respect to the signal integrity. These constraints have forced CAD design engineers to use via-in-pad plated over (VIPPO) structures in conjunction with traditional designs, such as dog bone traces, microvias, skipvias and pad-with-trace along with incorporating VIPPO back-drilling techniques in order to achieve routability and signal integrity requirements.

Under certain conditions, the use of VIPPO with other pad structures within a BGA footprint can result in a unique failure mode in which the BGA solder joint separates between the bulk solder and the intermetallic compound (IMC) either at the package pad or PCB pad interface, depending on whichever is the weaker interface. It can be either a complete or partial separation and hence, may or may not be detected at ICT/functional test. It is also extremely difficult to detect with inspection methods and is therefore a high risk for potential escapes to the field.

This solder separation occurs when the BGA component is subjected to a second reflow, i.e. during top-side SMT if the component is on the bottom-side of the board or during rework of an adjacent component. Details of the failure mode, including root cause hypothesis and specific case studies, will be discussed in this paper.

Test vehicles have also been designed to evaluate the influence of various package and PCB design parameters on this failure mode. These include BGA package body size, BGA pitch, VIPPO drill hole size, pad design (NSMD/SMD), microvia/skip via structures, backdrill depth, etc. Based on this work, PCB design guidelines have been established in order to characterize the limits and conditions for acceptable usage of VIPPO structures in order to prevent this type of failure mode from occurring in new product designs.

Key words: Via-in-pad plated over (VIPPO), Backdrill, Pb-free BGA, SMT, BGA rework

INTRODUCTION

As signal speeds and performance requirements continue to rise, the use of advanced PCB technologies is becoming increasingly important. As a result, the Via-In-Pad Plated Over (VIPPO) structure has been adopted in many BGA footprint designs within the PCB. These VIPPO structures are preferred over the more traditional dogbone pad structure in order to shrink signal path lengths, reducing two parasitic effects, capacitance and inductance, for improved high-speed performance. Figure 1 illustrates how the VIPPO structure can influence those parasitic effects. The signal traces, which connect the BGA pads with the vias, act as inductors. Additionally, as high-speed designs typically have ground planes immediately below the outer layer, there is also a capacitive effect that is generated. With the VIPPO structure, the outer trace layer is eliminated, thereby cancelling both parasitic effects.

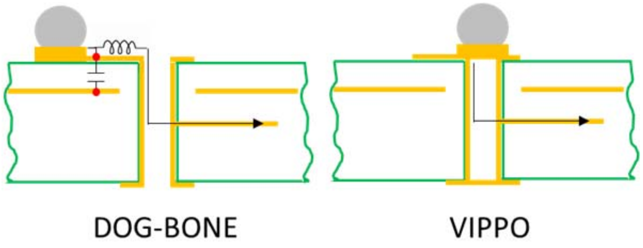

Figure 1. Dogbone vs. VIPPO Pad Structure

Figure 2 exhibits the VIPPO structure as compared with the VIPPO + backdrill (BD) structure. The use of backdrill with the VIPPO structure can eliminate the reflections within the unused portion of the via, which acts as a stub. The portion of the via indicated by the purple arrow is not "in series" with the signal path, but instead acts as a stub. Therefore, a portion of the signal is reflected back, creating an interference, which will degrade the high-speed signal performance. Hence, the purpose of the back-drill is to remove this "un-used" portion of the via in order to eliminate the reflections for a cleaner signal.

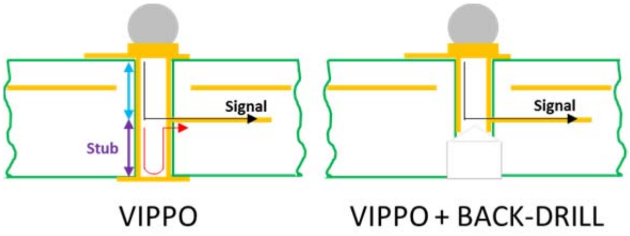

Figure 2. VIPPO vs. VIPPO + Backdrill Structure

With increased complexity of PCB designs for high-end networking products, the boards thicknesses are typically > 120 mils and signal speeds are reaching 25 GHz and beyond. For these types of designs, backdrilling of the VIPPO structures becomes imperative.

It is also a common practice to mix VIPPO and non-VIPPO pad structures within a single BGA footprint, as indicated in Figure 3. The green lines indicate a high-speed signal trace (e.g. for differential pairs) on the outer layer. It is preferable from a signal integrity perspective, to route these signal lines on the outer layers of the PCB to take advantage of microstrip routing which has faster propagation speeds than stripline routing. Hence, these BGA pads do not require the use of VIPPO. These non-VIPPO pads are highlighted in red. Without any VIPPO structure, a 'zero' stub length can be achieved, which is an extremely attractive option for the signal integrity engineer. Moreover, additional routing space is gained underneath the non-VIPPO pad. Unfortunately, these types of mixed footprint designs have a propensity for manufacturing defects during SMT assembly of BGA packages and can potentially expose the PCBA to field reliability risks if these defects escape manufacturing tests.

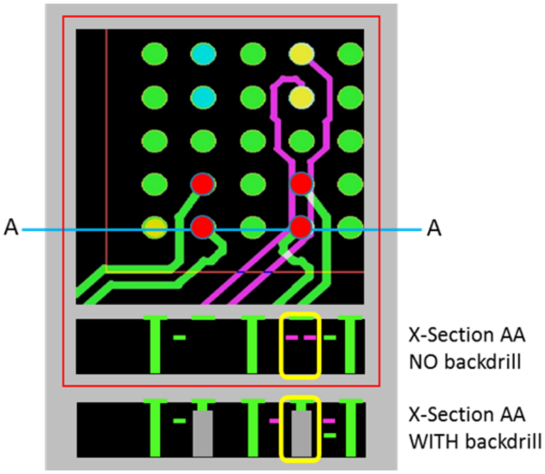

Figure 3. Mixed VIPPO/Non-VIPPO BGA Footprint

FAILURE MODE AND HISTORY

As a consequence of these advanced PCB technologies and complex board designs, a unique BGA solder joint failure mode has emerged during specific assembly conditions. This failure mode occurs when the bulk solder separates from the IMC during or just prior to reflow. This failure mode is of particular concern because the discontinuity is so small relative to the size of the solder joint itself that it cannot be detected via x-ray inspection methodologies. Furthermore, in many cases it is only a partial separation of the BGA solder joint and hence, it may not even be detected via ICT or functional test techniques. Without a robust methodology to screen for these defects, this presents an extremely high risk for potential escapes to the field.

Typically, this failure mode has been found on BGA packages with a 1mm pitch or less BGA array and having a PCB footprint that includes a mixed VIPPO/non-VIPPO pad design. The solder separation occurs when the component is subjected to a secondary reflow, either during top-side SMT for bottom-side components or during rework of an adjacent, or mirrored, BGA component. Since the open occurs between the bulk solder and the IMC, it does not have the typical brittle solder joint fracture signature, which has a flat fracture interface through the IMC as shown in Figure 4. Instead, this failure mode exhibits more of a hot solder tear or separation type of failure mode, as the solder separates from the IMC leaving it intact. [1,2,3] Figures 5 and 6 illustrate examples of both partial and complete solder separations. For these failures, the solder separation only occurs on the solder joints that use a VIPPO BGA pad and is typically adjacent to a solder joint(s) with a non-VIPPO BGA pad. In some cases, this type of failure mode has also been identified on a component having a full VIPPO BGA pad pattern on the PCB when there is also a pattern of VIPPO with deep backdrill (BD) within the footprint. Hence, the deep-backdrill VIPPO structures seem to mimic the behavior of the non-VIPPO pads so that it becomes comparable to a mixed VIPPO/non-VIPPO BGA pad footprint and again, induces solder separation in the solder joints on a VIPPO pad when subjected to a secondary reflow.

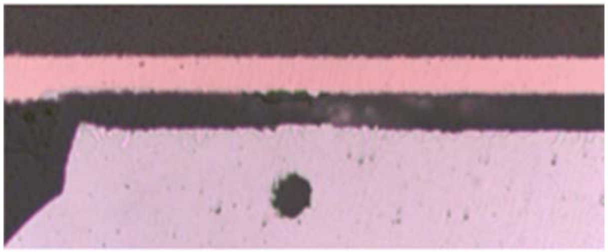

Figure 4. Example of Brittle Fracture

Since the separated solder ball shape is rounded near the open or partially open interface, this indicates that the solder joint underwent reflow subsequent to the separation. Furthermore, since the separation is between the bulk solder and the IMC and does not reflect a brittle fracture, it is suspected that the separation occurred after the solder has softened and is nearly molten. Figure 6 illustrates a brittle solder joint failure in which the fracture occurs within the IMC itself and exhibits more of a flat surface indicative of crack propagation.

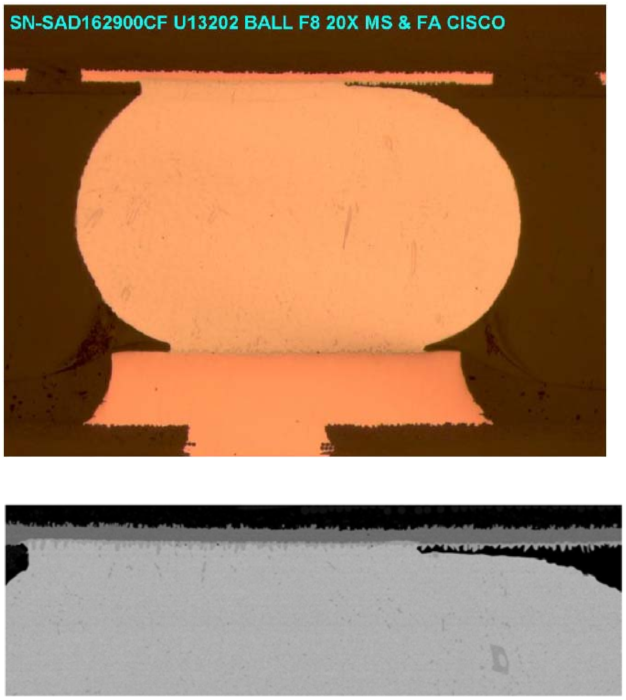

Figure 5. Partial Solder Separation

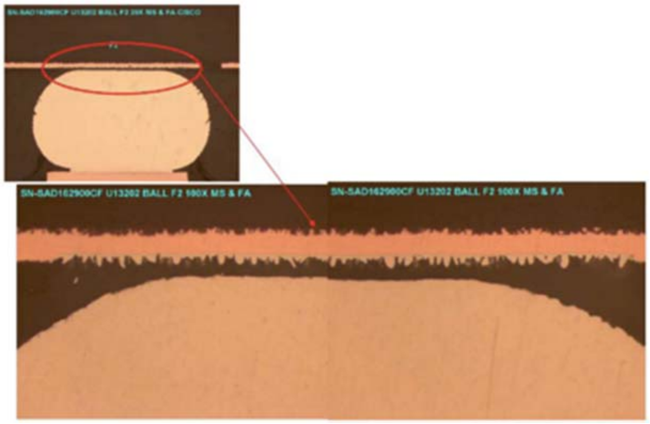

Figure 6. Complete Solder Separation

FAILURE MECHANISM

There seem to be two primary effects that are occurring which contribute to this failure mechanism. First, there is a CTE mismatch between the VIPPO structure and the non-VIPPO, or deep-backdrill VIPPO, structure, that results in a greater expansion of the PCB beneath the non-VIPPO BGA pad, or the deep-backdrill VIPPO pad, as compared with the VIPPO BGA pad. Secondly, the higher thermal conductivity of the VIPPO structure as compared with the non-VIPPO, or deep-backdrill VIPPO structure, allows the VIPPO solder joints to reach liquidus before the adjacent solder joints having a non-VIPPO, or deep-backdrill VIPPO pad. Therefore, during a secondary reflow process, when the adjacent non-VIPPO solder joints are still solid, tensile stresses are induced in the VIPPO solder joints as the adjacent non-VIPPO solder joints are pushed up due to the greater out-of-plane PCB expansion beneath those pads. Subsequently, when the VIPPO solder joints become molten, these high stresses are relieved as the bulk solder ‘tears’ or separates from the IMC. This solder separation can occur at either the package interface or the PCB interface of the solder joint, depending on whichever is the weaker interface. Since the PCB pad design is generally a non-soldermask-defined pad (NSMD) and the BGA package typically uses soldermask-defined pads (SMD), the separation will more likely occur at the package interface.

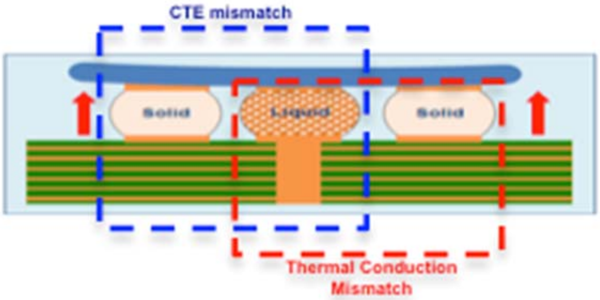

Figure 7. CTE Mismatch Between VIPPO and Adjacent Non-VIPPO Structures

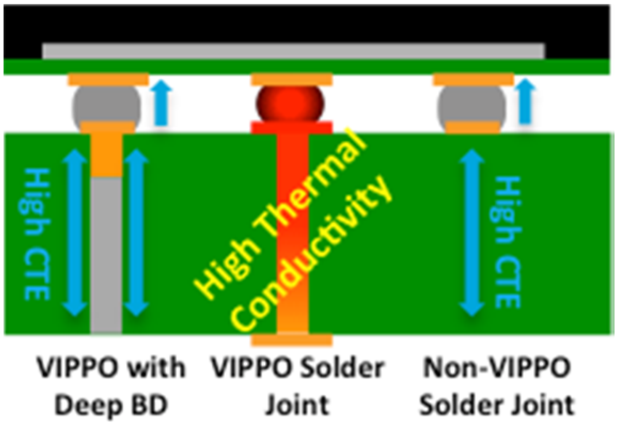

Figure 8. Thermal Gradient Between VIPPO and Non-VIPPO Structures

Alternatively, a 100% VIPPO BGA footprint without deep backdrill does not introduce the additional stresses that are exhibited with the CTE mismatch between adjacent VIPPO and non-VIPPO pad designs. Additionally, a 100% VIPPO BGA footprint without deep backdrill does not create the high thermal gradients between adjacent solder joints that the mixed VIPPO/non-VIPPO BGA footprints achieve. Therefore, this type of failure mode has not been identified with 100% VIPPO BGA footprints with no deep backdrill.

EVALUATION PLAN

In order to better understand the influence of various PCB and packaging design parameters on this failure mode, 3 different test vehicles have been designed to assess the following:

1. Influence of drill hole size (DHS) for the VIPPO structures: 9.8 mils vs. 7.9 mils DHS
2. Influence of BGA package body size and BGA pitch
3. Influence of varying backdrill (BD) depths and BGA package body size

Each test vehicle is assembled through a primary and secondary SMT attach process, followed by inspection and physical analysis to validate the solder joint integrity after each reflow. The printed circuit assembly equipment, process parameters, tooling (e.g. stencil design and technology), assembly materials (e.g. solder paste) and inspection equipment and methodologies utilized for these builds are consistent with Cisco's standard production processes in order to minimize the number of variables introduced in this study.

TEST VEHICLES

The DDR4 VIPPO and non-VIPPO test vehicle (shown in Figure 9) is designed to investigate the influence of two different VIPPO drill hole sizes (DHS), 9.8 mils & 7.9 mils, on the solder joint integrity in a mixed VIPPO and non-VIPPO BGA footprint within the PCB. A set of controlled PCB factors such as PCB thickness (125 mils), material (Megtron 6) and number of stack-up layers (16) are used along with DDR4 daisy chain BGA components (13.3 x. 7.5 mm sq., 0.8mm pitch) for resistance measurement and failure analysis purposes. The DDR4 components are designed only for single-side PCB assembly. However, for this evaluation, the assembled PCB is subjected to a second SMT reflow excursion in order to simulate a secondary top-side reflow process.

The fine pitch VIPPO and non-VIPPO test vehicle (shown in Figure 10) is used to study the impact of different BGA body sizes, ranging from 10x10 mm sq. up to 37x37 mm sq., in addition to BGA pitches, ranging from 0.7mm to 1.0 mm, with respect to the solder joint integrity within a mixed VIPPO and non-VIPPO BGA footprint on the PCB. An advanced 7.9 mil DHS VIPPO was used in order to accommodate the DHS-to-pad size design rule for BGA pitches < 1.0 mm. The components are designed on both sides of the PCB and utilize the same set of controlled PCB factors as defined in the DDR4 test vehicle for thickness, material and stack-up.

Lastly, the VIPPO and VIPPO + backdrill test vehicle (shown in Figure 11) is designed to investigate the influence of a mixed VIPPO and VIPPO + backdrill BGA footprint on the solder joint integrity. Different backdrill depths (to layer 03, layer05 and layer07 on a 28-layer, 130 mil thick PCB design) are studied based on PCB backdrilling depth capability and tolerance. Different daisy chain component BGA body sizes ranging from 10x10 mm sq. to 37x37 mm sq. are again used for this test vehicle.

For all of these test vehicles, each board is subjected to pre and post assembly (i.e. after primary and secondary reflow processes) process resistance measurement followed by physical analysis verification with dye & pry and cross-section techniques.

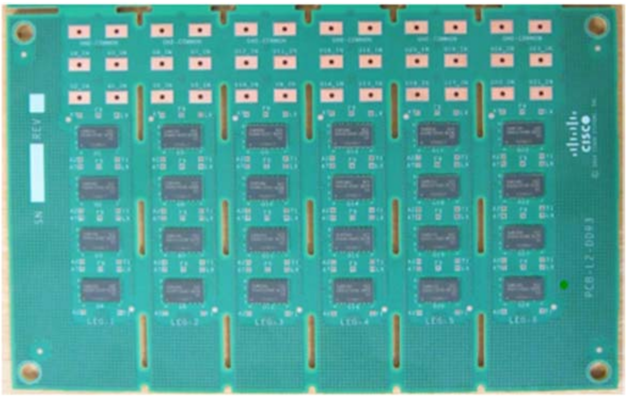

Figure 9. Mixed VIPPO and Non-VIPPO Test Vehicle With Multi-Drill Size

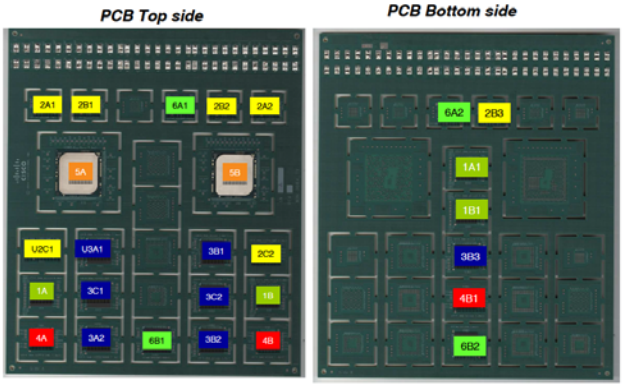

Figure 10. Mixed VIPPO and Non-VIPPO Test Vehicle With Multi-Package Types

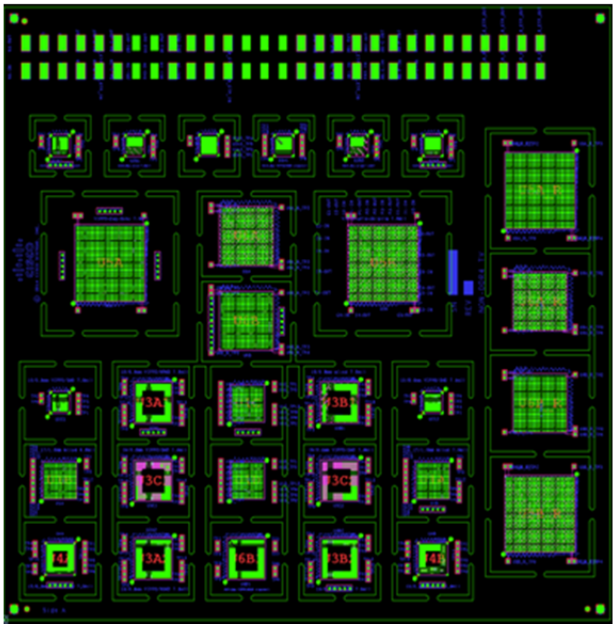

Figure 11. Mixed VIPPO and VIPPO with Backdrill Test Vehicle With Multi-Package Types

RESULTS AND DISCUSSION

DDR4 Test Vehicle

Mixed VIPPO and non-VIPPO BGA footprints with different drill hole sizes were directly compared for this DDR4 test vehicle study. Post secondary SMT reflow electrical resistance measurements were taken and physical analysis via dye and pry was performed for solder separation failure verification. The experimental control test leg with an all VIPPO pad BGA footprint showed no solder cracks. On the other hand, as shown in Figure 12, all of the designs with mixed VIPPO and non-VIPPO pads within the BGA footprint showed solder separation at the component side of the VIPPO solder joint. The solder separation failure occurred with both 7.9mil and 9.8mil drill hole sizes, and hence, confirms that the failure mechanism is independent of drill hole size used in the VIPPO pad structure.

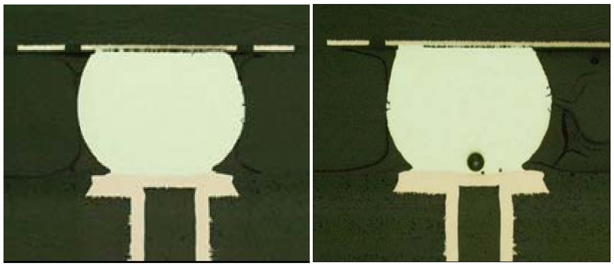

Figure 12. VIPPO Pads with 9.8mil and 7.9mil DHS Post 2nd Reflow.

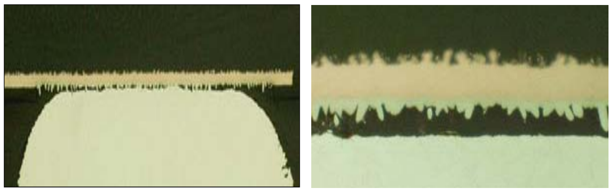

Figure 13. Solder Separation Interface Observed on DDR4 VIPPO + Non-VIPPO Test Vehicle

Fine Pitch VIPPO and non-VIPPO Test Vehicle

Employing the same analysis technique, the results obtained for the fine-pitch, mixed BGA VIPPO and non-VIPPO study further confirmed that mixed VIPPO and non-VIPPO pad designs within the same BGA array would result in solder separation at the component side and is independent of BGA pitch and VIPPO drill hole size. However, the data also indicates that BGA body size can influence the outcome of the solder joint integrity for this type of defect.

This experiment studied 10x10 mm sq., 15x15 mm sq., 17x17 mm sq., 19x19 mm sq. and 37x37 mm sq. package body sizes, and only the 37x37 mm sq. package body size did not result in this solder separation failure mode with the mixed VIPPO and non-VIPPO BGA footprint. However, additional work will be needed to better understand the influence of the package body size on this defect and to determine where the “cutoff”, or threshold, body size should be defined. Although, the underlying root cause as to why the large body size tends to perform better is not clearly understood, it is hypothesized to be related to the package weight, BGA density and possibly the ratio and locations of the VIPPO-to-non-VIPPO solder joints within the BGA array. The larger 37 mm sq. FCBGA package is much heavier than the smaller overmolded BGA components included on this test vehicle and hence, may require more strain per solder joint to separate from the IMC. This 37 mm sq. package also has a higher BGA density due to its fine pitch (down to 0.7mm pitch) and exhibits a lower ratio of VIPPO-to-non-VIPPO pads within the BGA footprint as compared with the smaller BGA packages studied. Furthermore, the locations of the VIPPO pads are grouped together rather then being dispersed among the non-VIPPO pads as seen with the smaller BGA components. This is illustrated in Figure 14 below, showing the non-VIPPO pads connected to a plated through-hole (PTH) in green. Having fewer non-VIPPO pads surrounding the VIPPO pads may induce less strain within the VIPPO solder joints resulting in less likelihood for solder separation for the 37 mm sq. component. Further work in this area should be pursued in order to better understand the influence of these parameters.

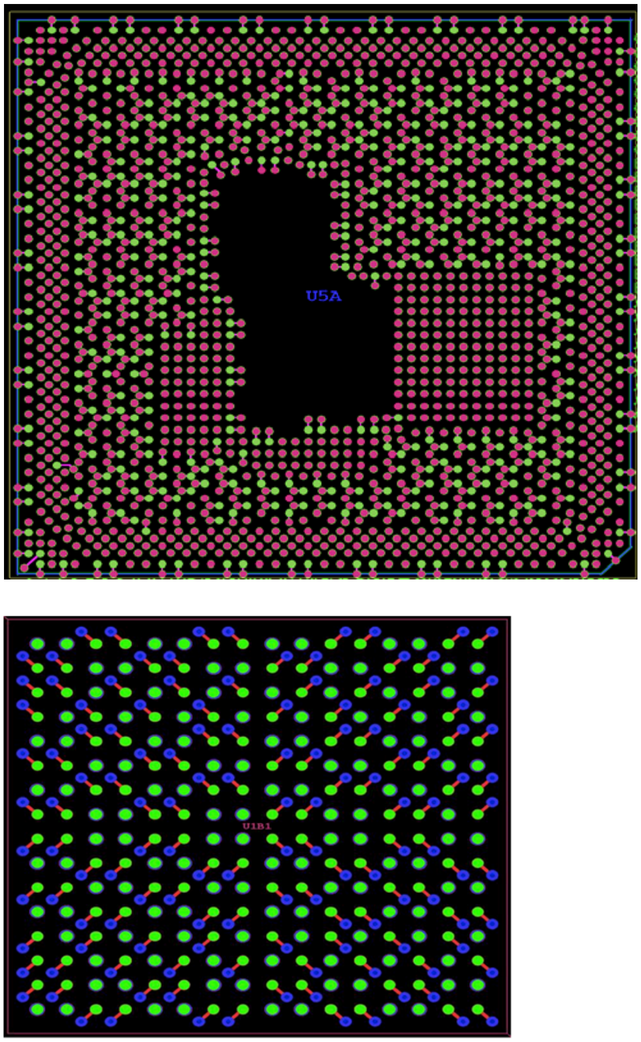

Figure 14. 37x37mm sq. Variable Pitch BGA Footprint vs. 17x17mm sq. BGA Footprint

VIPPO and VIPPO + Backdrill Test Vehicle

A VIPPO pad with a certain level of backdrilling depth is expected to behave similarly to a non-VIPPO pad. Currently, besides the floating pad with traces, non-VIPPO pads are also defined as pads with microvias (layer 1 to layer 2 via) or skip-vias (layer 1 to layer 3 via). BGA footprint designs combining VIPPO and any of these non-VIPPO pads have been demonstrated to exhibit the solder separation failure mechanism. Therefore, BGA footprint designs with mixed VIPPO and VIPPO + back drilling to some threshold depth would be expected to behave similarly, exhibiting the same solder separation mechanism as seen with these standard mixed VIPPO and non-VIPPO BGA footprint designs. Therefore, the objective of this test vehicle is to understand what this backdrill depth threshold should be within a VIPPO and VIPPO + backdrill BGA footprint in order to prevent the solder separation failure mechanism from occurring. Results from this test vehicle will be used to provide a guideline for future PCB designs with VIPPO and VIPPO + backdrill BGA patterns. However, the experimental results from this investigation are still pending as the data collection and interpretation is still on-going.

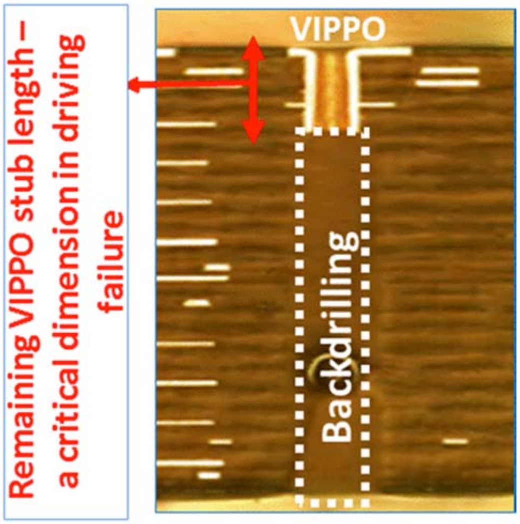

Figure 15. VIPPO Stub Length after Backdrill

DESIGN GUIDELINES

The test vehicle experimental data discussed previously has provided a good baseline understanding and insight into the parameters influencing this solder separation failure mode. Because this solder separation failure mode can result in an electrical failure either at manufacturing test or prematurely during field use, it poses a high risk for product launch in terms of solder joint quality and reliability. This establishes the need for specific design guidelines with the use of VIPPO pads. Based on the experimental data thus far, mixed VIPPO and non-VIPPO pad designs within a single BGA footprint are prohibited for applications having a secondary SMT process. For designs having only a single SMT reflow process, the rework process of an adjacent component can still pose a high-risk for solder separation of the adjacent non-reworked component having a mixed VIPPO and non-VIPPO BGA footprint. Therefore, a validated mitigation strategy is required for manufacturing production release of such designs. There is also on-going work to establish more data with the VIPPO and VIPPO + backdrill pad designs within a single BGA footprint in order to define an acceptable backdrill depth limit which does not induce the solder joint separation failure mechanism.

SUMMARY AND CONCLUSIONS

This work has evaluated various BGA packaging and PCB design parameters in order to characterize their influence on this double-reflow solder separation failure mode for mixed VIPPO BGA pad footprints. It was observed that this failure mode is not dependent on the BGA pitch and can occur for ≤ 1.0 mm pitch components. It was also found to be independent of the VIPPO drill hole size, occurring with both 9.8 and 7.9 mil drill hole sizes. However, this failure mode has been shown to be sensitive to the BGA package body size, with the risk of occurrence decreasing for large package body sizes. It is also suspected that the package weight, BGA density and ratio and location of VIPPO-to-non-VIPPO pads within the BGA array may also play a role along with the package body size.

As previously noted, the current guidance recommends not to mix the VIPPO pad structures with non-VIPPO pads or deep-backdrill VIPPO structures within a single BGA footprint. Further investigations are still needed to establish more specific guidance regarding the usage of these VIPPO structures with non-VIPPO pad designs or deep-backdrill VIPPO structures. As performance requirements continue to advance, these types of PCB structures and designs will become a necessity for future generations of products. Hence, these design guidelines provide only a short-term solution to address this failure mode. More detailed understanding of the mechanisms driving this failure mode and how to control them are needed to develop a long-term solution that can allow implementation of these mixed VIPPO designs.

FUTURE WORK

As discussed in this paper, this work has helped to establish PCB design guidelines and best practices in order to prevent this defect from occurring in new product designs. However, there are also other approaches being investigated as potential mitigation strategies that directly address the theorized root cause by employing innovative assembly processes. Positive results have been demonstrated thus far, and more data is being generated before pursuing publication of this work.

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