Lessons Learned While Investigating Microvia Reliability Failures.

Tobias Bernhard, Roger Massey, Senguel Karasahin, Frank Brüning
Atotech GmbH, Berlin, Germany

Abstract.
Micro vias, be they mechanically, or more typically laser drilled have revolutionized the technical capabilities of today PCBs. Their high hit rate, and low-cost during manufacture, in combination with their small real estate requirements enable the High-Density Interconnects that have allowed PCB and product designers to push their applications to capabilities beyond anything thought possible with more traditional drilling techniques. That being said, with their number easily running into the many 1000s in a single PCB assembly, there is increasing concern about the long-term reliability of micro vias, especially when used in a stacked configuration.

Over the last few years, there has been a slow, but increasing number of reports concluding that stacked micro vias are failing preferentially when compared to an alternative staggered via design. However, while a staggered interconnect arrangement could be seen as a solution to satisfy the reliability demands, they are usually undesirable as they consume larger amounts of real estate which can't be tolerated in many applications.

With strong evidence available, the preferential failure of stacked micro vias can't be denied, and as such, there is now a growing number of investigations ongoing to examine microvia reliability and determine if and why staggered micro vias fail preferentially, and also trying to identify what is the ideal microvia structure for best reliability performance.

As a result of the ongoing need to understand the nature of any failure, there is an ever-increasing array of analysis tools being drawn on in order to inspect microvia structures. Optical microscopy has in many cases been superseded by the Scanning Electron Microscope, and the SEM is now being supplemented with other tools such as the Focused Ion Beam Microscope and Tunneling Electron Microscope to name a few. However, with each new analysis tool there comes a wealth of new information, and this needs to be understood and interpreted before that information can be valuable.

As part of investigations into microvia failures, we review the published data and find that while these new analysis tools are being readily used, there is what we consider to be some misinterpretation of the data, leading to inaccurate route cause diagnosis, and conclusions that are questionable at best, or wrong and misleading at the worst.

This paper summarizes these initial investigations and discusses the misinterpretation of data as well as offering some insight into other microstructural characteristics which will likely impact the physical properties and reliability of plated blind micro vias.

Background.
Mechanical and laser formed blind micro vias (BMV) have become a standard technology for high density PCB applications as their minimal footprint enables numerous real estate savings compared to traditional through hole techniques. While the use of staggered patterns (Figure 1a) is still widely used, this approach requires a larger footprint compared to an equivalent stacked approach (Figure 1b) and so the use of stacked BMVs has become the state of the art solution where the highest PCB densities are needed.

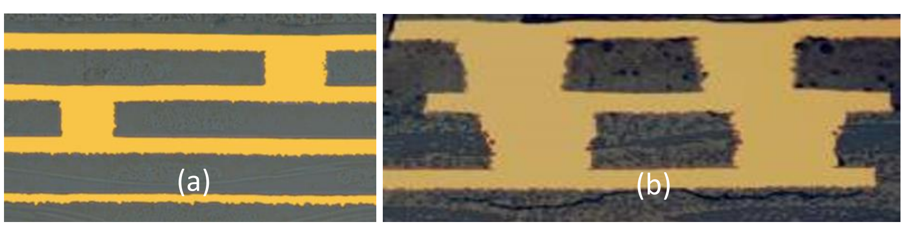

Figure 1. Staggered (a) and Stacked (b) BMV Layouts.

As with all production processes, there is a learning curve, in-which, products are initially prone to increased production variances, which lead to performance and quality issues, and as is normal, these diminish over time until a high volume, high reliability process is established. Laser drilled BMVs have undergone such a cycle, with BMVs generally now being considered as a robust interconnect method. As mentioned previously, stacked BMVs are often preferred by product designers as they utilize not only a smaller footprint, enable higher track densities with smaller pad pitch, but also allow for enhanced thermal paths which are also a necessity in many modern electronics units where, heat flow can be as critical as electrical flow.

One ongoing concern with stacked BMVs is the impact arising from heat, namely the expansion which occurs during PCB assembly as well as once those populated PCBs reach their final service application. With a series of stacked BMVs being essentially a "solid" column of Copper, the thermo-mechanical properties of the BMV stack is dramatically different to that of the surrounding dielectric matrix, and so there is understanding that significant stresses can arise at the interfaces between each individual via as well as between the complete stack and its encapsulating glass/epoxy resin. While this concern has always existed, and it has been proven to exist, where there have been concerns for final product reliability, it has been found that a staggered BMV pattern can accommodate the applied thermal strains and offer an improved product lifetime, and so have been adopted. Unfortunately, with modern electronic applications demanding the highest possible densification in the smallest possible area, the use of staggered BMV designs is becoming unacceptable and the need for a high reliability stacked BMV design is re-emerging. It must be pointed out however, that stacked BMVs are very widely used within many of today's PCB designs without excessive field or assembly failures, however, there are increased reliability applications such aeronautics, space and military, where there is a rapidly growing concern over the long term reliability of stacked BMVs.

It is fair to say that while this concern has been steadily increasing, it has been predominantly within those users located in the USA, however, with many PCB users and producers now having a presence and operations in many countries, this concern has begun to spread and has become more of a global issue than it has been in the past.

In mid-2018 IPC released a white paper[1] which as its name implies raised a "call to arms" among the PCB industry as a whole, to review the performance of BMVs, and since that time, there have been an increasing number of papers at technical conferences reiterating and highlighting the need to investigate BMVs further.[2]

This paper, summarizes a number of investigation techniques used when examining failures occurring within stacked BMVs following thermal screening, or during field service, and highlights the need for the correct analytical tools to be used otherwise there is a risk of root cause being incorrectly identified.

Micro Via Formation and Failure.
There are multiple specific methods, for the formation of a BMVs during PCB production, however such methods can generally be summarized into a generic process flow as shown in Figure 2, it should be noted that there are no significant differences depending on whether the via itself is formed through mechanical drilling or laser ablation.

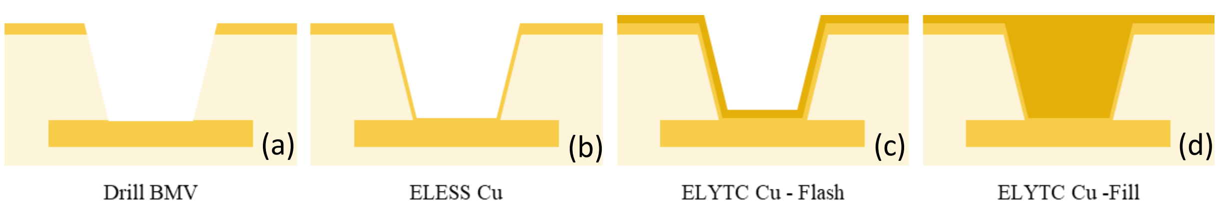

Figure 2. Generic Process Flow for Plated BMV Production.

In terms of failures exhibited by BMVs, the most commonly reported is one referred to as capture, or target pad separation, an example of which can be seen in Figure 3a. For such failures, it is typically found that the failure occurs at the base of the BMV where the plated deposit connects with the previously formed target pad.

From Figure 2 it is clear that this target pad to plated layer interface is a complex structure comprising of the target pad itself, underlying an electroless Copper (ELESS Cu) or other metallization layer, which is then covered with an electrolytic plated Copper (ELYTC Cu) layer, (Figure 3b), as such, it can be appreciated that there are multiple potential locations for failure. (Table 1)

Table 1 - Potential Failure Locations for Plated BMVs.

1	Within the capture pad
2	At the capture pad – ELESS Cu interface
3	Within the ELESS Cu layer
4	At the ELESS - ELYTC Cu interface
5	Within the ELYTC Cu deposit

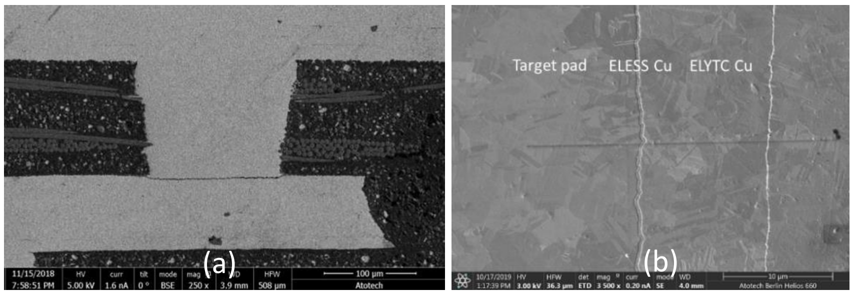

Figure 3. Typical Failure of a BMV at the Target Pad (a) and SEM Showing Target Pad – ELESS Cu – ELYTC Cu Structure. (b)

While failure at locations 1 and 5 in Table 1 are possible, they are rarely reported, with the most common failures being attributed to poor "adhesion" of the ELESS and/or ELYTC Cu, or failure within the ELESS Cu itself, although this is rarely so simple to identify.

Typical Investigation Techniques.
As its name suggest "failure analysis" (FA) occurs after a component has failed, and as such offers a vital insight into why that component did fail. Historically, FA has made use of cross sectioning to gain access to the point of failure, followed by optical microscopy, and over time this has been supported or even replaced by Scanning Electron Microscopy (SEM) which offers not only much higher magnifications but elemental detection and analysis.

Electro Polishing.
Mechanical polishing followed by chemical etching is a widely utilized technique, and will likely remain one of the initial methods of sample investigation, however, this can be considered a "macro" process as there can be substantial amounts of material removed. A more "refined" method, which can still be used in combination with SEM etc, is that of electro polishing. This is still considered an etching process, but the material removal is significantly lower than that with wet etching, and can lead to significant inspection benefits, which may be missed through other techniques. As with most etch type operations, the degree of etch penetration or treatment, varies depending upon the properties of the material being treated, so electro polishing, can often highlight interfaces between complex layered structures like those at the base of a BMV.

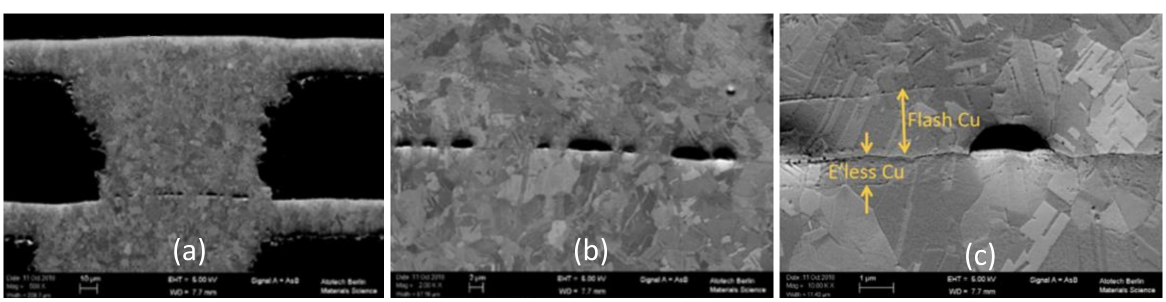

Figure 4. SEM Images of an Electro Polished Sample.

From Figure 4a and 4b it is clear that there is a line of voids at the base of the BMV, what is not known however, is the exact location of those voids, namely do they occur at the target pad – ELESS Cu interface, within the ELESS Cu layer itself, at the ELESS Cu – ELYTC Cu interface, or within the bulk plated Cu? This knowledge is essential in understanding the root cause of the defects, and identifying the process area in need of troubleshooting activities. Following the electro polishing operation, it becomes possible to distinguish the boundaries where the target pad, ELESS and ELYTC Cu layers occur. In view of this, in Figure 4c, it is clear that the line of voids occur not at the target pad – ELESS Cu interface as is often assumed, but actually at the ELESS Cu – ELYTC Cu interface.

Scanning Electron Microscopy with Focus Ion Beam.

It is reasonable to state that SEM has become a standard technique used during surface failure analysis, yet, more recently there has been a wider adoption of SEM utilizing a Focus Ion Beam (FIB) as this allows selective removal of material and offers additional inspection "within" the sample that is not possible with surface techniques such as standalone SEM (Figure 4). SEM-FIB has been used within the IC fab environment for many years, and is now gaining in popularity within, but is still not common, to the PCB industry.

In order to open up such an inspection window in the sample, an incidental ion beam is used to "mill" or ablate material, and through automated scanning of the ion beam, a high level of control can be achieved, enabling detailed penetration into the sample.

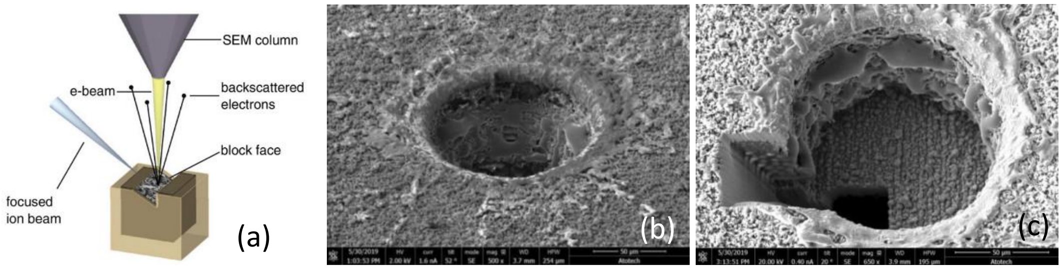

Figure 5. Schematic of SEM-FIB (a) Typical SEM Images (b) and SEM-FIB (c) Showing Location of Ion Milling Window.

One of the first points typically noted during FA of BMVs is the general crystal structure within the plated Copper, and this generally falls into 2 distinct groups. The first showing a single uniform crystal structure where the interface between the target pad and the plated Cu cannot be distinguished (Figure 6a), or a structure where there is a break in the crystal continuity and one or more clear interfaces can be seen (Figure 6b) While, it could be argued which of the two structures would offer the "best" reliability performance, it is offered that a single crystal pattern would be preferential, as any marked changes in crystal structure would generally enable some form of stress concentration, and could exacerbate failure. It should also be considered, that such changes in structure typically occur around the target pad – ELESS Cu – ELYTC Cu interfaces, and as this is commonly the point of BMV failure, it would be sensible to propose that a continuous metallography would be desirable.

Such structures arise due to the crystallization of plated deposits that occurs following plating. Immediately after deposition the plated layer has no defined crystal structure, but will begin to develop one over a period of time, ideally this recrystallization occurs in a "bottom up" fashion, with each new layer following the crystal orientation of the underlying layer, i.e. the ELESS Cu continues the orientation of the target pad Cu, and then the ELYTC Cu follows the orientation of the ELESS Cu layer. Known as epitaxial growth, this process occurs naturally, although it should be acknowledged that there are influences within the process and the chemical constitution of the plating chemistries which can impact the recrystallization characteristics of plated layers.

While optical microscopy and SEM, in combination with etching processes will enable inspection of a BMV crystal structure, SEM-FIB is becoming a popular means to achieve this as, once the ion milling has opened the inspection surface, there is no need for secondary etching and there is minimal risk of over or under etch leading to ambiguous results.

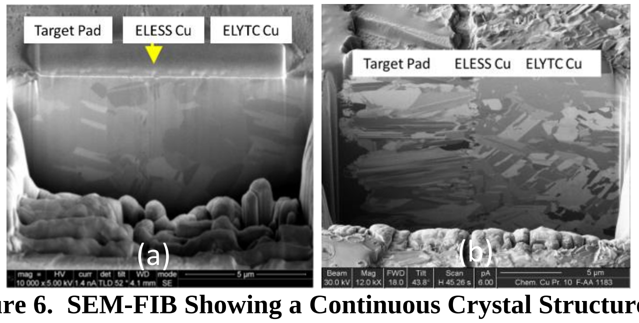

Figure 6. SEM-FIB Showing a Continuous Crystal Structure (a) and Dis Continuous Crystal Structure (b) across the BMV.

Possible Mis-Categorization with SEM-FIB.

As discussed previously, SEM-FIB enables removal of the sample material in a direction normal to the sample surface. The major benefit of utilizing such a "FIB cut" is that it can reveal features within a sample that may otherwise be damaged or influenced through traditional methods such as cross sectioning.

One point to consider, and is often overlooked, is the removal of the sample material itself during the "cut" or milling operation, and where that material goes once it has lifted from the sample. As with all SEM units, there is a series of vacuum and detector systems that remove and make use of these "sample" streams, yet the volume of material removed during a FIB-cut is substantially higher than that created when performing simple elemental analysis, yet it is assumed that the operating vacuum and exhaust system in the SEM chamber is sufficient to accommodate this high material removal rate, yet this is not necessarily the case.

Figure 6 shows a prepared SEM-FIB sample, where the initial "cut" has been made manually in order to approach a Copper filled Through Silicon Via (TSV) Once the TSV has been reached, the automatic milling and serial imaging process was begun. During this automatic operation there are two major points of note.

1. As expected, the Cu filled TSVs become revealed as the cut proceeds through the sample
2. There is build-up of material occurring within the milling box as the operation occurs.
    a. At 0 automatic slices, there is no material visible in the milling box
    b. After 80 slices, redeposition can be seen on the side walls of the milling box
    c. After 160 slices, there is moderate redeposition in the milling box
    d. After 240 slices, there is significant redeposition in the milling box

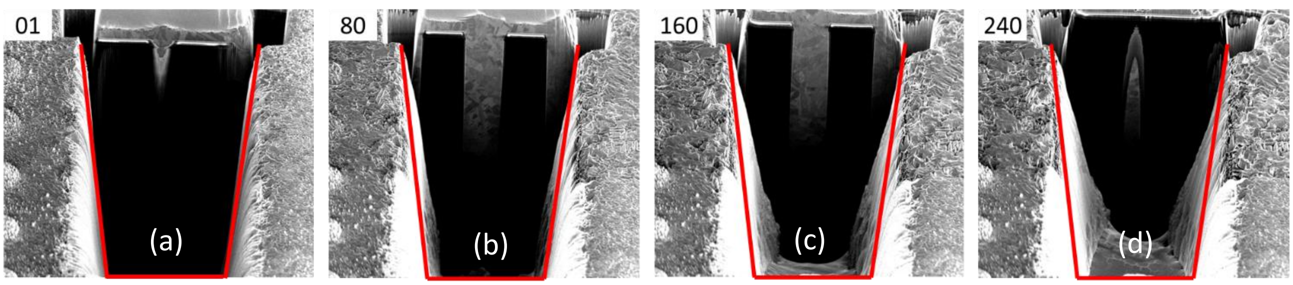

Figure 7. SEM-FIB Images Recorded During an Automatic Milling Operation Showing Redeposition and Buildup of Removed Material.

It is point 2 that is of most interest as this material build up contains the plated Cu from within the TSV itself. As such, it is a redeposition of the material removed during the cut or milling operation. For the images shown, the redeposition was not considered an issue as it did not impact the investigation being made, as there were no structural defects within the TSV itself, but when such a technique is used to investigate a cracked BMV, there is a serious cause for concern.

The primary requirement during FA is that the techniques used do not influence, or change the sample being inspected, otherwise there is a strong likelihood that the collected data can be misleading. If material redeposits on the sample during a FIB-SEM investigation then this primary requirement is broken, and the conclusions drawn from the analysis must come under question. In the case of a cracked BMV, there is a very high likely hood that the redeposition will occur not only within the milling box but within the crack under investigation, in view of this, the crack may appear to be coated with Cu which can be mis-interpreted as a defined layer or coating.

Figure 8 shows a series of SEM-FIB images taken while investigating a failed BMV joint, clearly the point of failure is located at the base of the BMV and it would be reasonable to anticipate that it would be located close to, or cognizant with one of the target pad – ELESS Cu – ELYTC Cu junctions. Through the use of an automated milling procedure, an inspection plane normal to the crack has been created. In Figures 8c and 8d there appears to be a distinct layer of material on either side of the failure crack, and when measured, this is found to be approximately, 1um in thickness, which is comparable to that of the deposited ELESS Cu layer. As such it would be reasonable to conclude that the crack arose due to cohesive failure within the ELESS Cu layer as this can be clearly seen on either side of the crack surface.

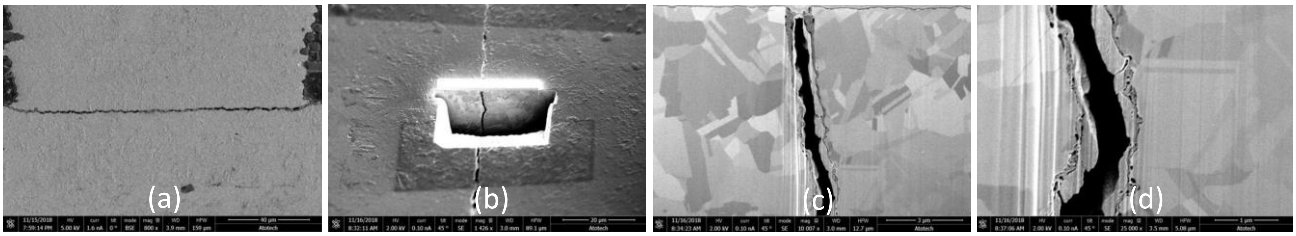

Figure 8. Series of SEM-FIB Images Investigating BMV Failure.

In order to support this conclusion it would be beneficial if some additional analysis could be performed in order to locate and confirm the ELESS Cu layer, and typically this would be supplied through Energy-Dispersive X-ray spectroscopy (EDX) targeting elements unique to the ELESS Cu process. In such cases, Palladium or Nickel would be suitable; Pd is commonly used as a catalytic seed layer, so its presence can be used as a reference from which the location of the ELESS Cu layer can be determined, and in the case of Ni, it is often co-deposited with the Cu in order to influence the physical properties of the final ELESS Cu layer, and so, Ni presence can directly indicate the location of the ELESS Cu layer itself. Unfortunately the energy of the incidental electron beam used in SEM-EDX investigations is of a sufficiently high order that the beam penetration can be in excess of 1um in depth, resulting with a high “background” reading. In the case of BMVs, this means that there is a high Cu measurement, and a very low, or no concentration of Pd or Ni detected, thus making ELESS Cu location extremely challenging. When this occurs, without the supporting elemental evidence, the original conclusion would remain, and the failure is attributed to a “brittle” ELESS Cu layer, which would subsequently generate investigations and actions focused around the applicable process.

Transmission Electron Microscopy.

With the limitations noted above in relation to SEM and SEM-FIB, the use of Transmission Electron Microscopy (TEM) now becomes attractive as the technique offers a lower detection limit for elemental analysis, potentially useful in identifying Pd and Ni in ELESS Cu layers, as well as a higher resolution which may yield more clear details on metallographic features in and around the BMV failure.

As the name, suggests, TEM is a transmission method, meaning that the detectors are typically positioned beyond the sample, and they collect particles following their transport *through* the sample, unlike SEM where the detectors are commonly in front of the sample and collect particles that have been scattered, reflected or emitted *off* the sample surface. TEM does require specialist sample preparation, typically involving SEM-FIB to cut a thin lamellae which can then be examined transmissibly. (Figure 8)

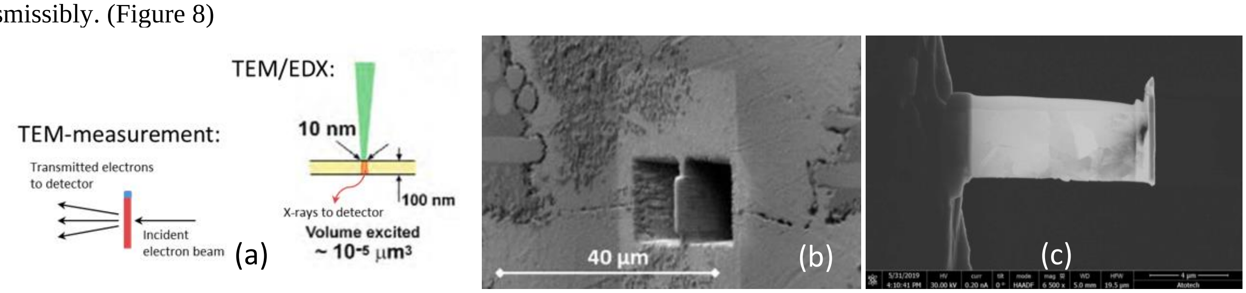

Figure 9. Schematic of TEM Technique (a) In Situ TEM Lamellae Preparation with FIB (b) and Lamellae After Removal from Sample. (c)

As a TEM sample is substantially thinner than a SEM sample, in the region of 50-100nm, there is a much lower effective beam penetration depth compared to SEM, thus enabling a lower “background” analysis during EDX and an increased elemental sensitivity detection, meaning that the lower Pd and Ni contents in an ELESS Cu deposit are more likely to be detected.

Figure 10 shows representative results through TEM investigations, and as can be seen, the primary image in combination with the EDX analysis allows relative locations of the ELESS and ELYTC Cu layers to be determined.

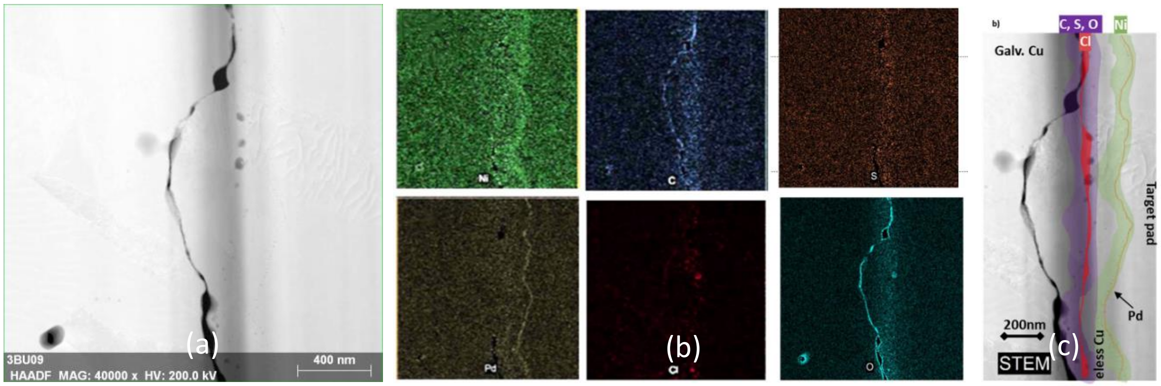

Figure 10. TEM Images of Sample (a) with Elemental Analysis (b) Aiding Layer Location. (c)

If we now refer back to the example in Figure 8 where the BMV failure is attributed to cohesive failure within the ELESS Cu layer. Through TEM analysis, we can now determine the location of the ELESS Cu layer itself, which, as shown in figure 11b, is found to be not only wholly intact but located to the left side of the crack, implying that the material found on the inner faces of the fracture surface are in fact redeposited artifacts arising from the FIB cut. In view of this, it can now be concluded that the BMV failure itself could be associated with adhesive failure between the ELESS Cu and ELYTC Cu layers.

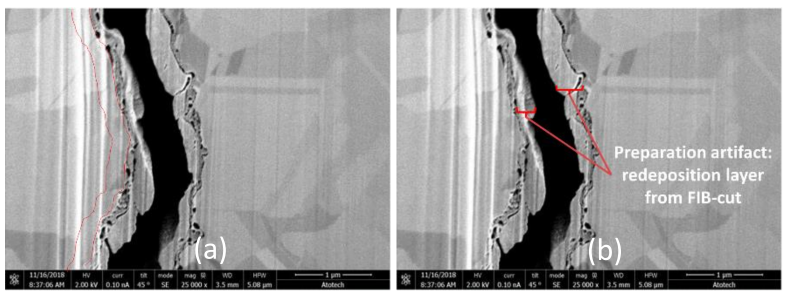

Figure 11. SEM Image with TEM Based Overlay Showing Location of ELESS Cu Layer (a) and Preparation Artifact from FIB Cut. (b)

Similar to most microscopy methods, TEM has a number of applicable inspection techniques, including "Bright" and "Dark Field", BF and DF respectively. When utilizing BF, the detectors receive a high intensity of directly transmitted electrons, enabling good clarity of crystal orientation, whilst DF has a lower intensity of scattered electrons, making it more suitable for detection of small voids etc within the sample. (Figure 12)

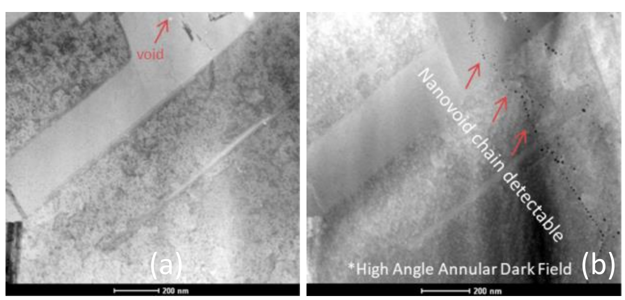

Figure 12. Bright (a) and Dark Field (b) Images of the Same TEM Sample. BF Highlights Crystal Orientation whilst DF Enhances Void Detection.

We have reported elsewhere[3,4,5] on the presence of nano voids found during TEM-DF investigations, and this has led to a unique and increased understanding on potential failure mechanisms for BMV structures, but has importantly also enabled us to offer a "best practice" process for similar investigations.

Suggested "Best Practice" for BMV Failure Inspection.

As would be expected, a recommended analytic approach is a sequential operation, with each step in the sequence building on the knowledge gained from the preceding step.

It should be noted that investigations of separated joints with visible cracks is not recommended, due to preparation artefacts from cross sectioning and the high potential for redeposition layers forming during ion milling operations with SEM-FIB. However, if this is not possible, care should be taken to ensure that such artefacts do not lead to misleading conclusions.

Step 1 – Optical Microscopy.
Determine general presence and location of point of interest.
Chemical etching can yield additional data regarding basic crystal structures.

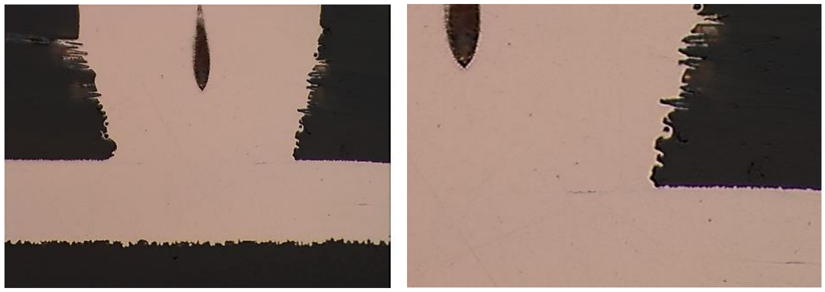

Figure 13. Optical Images of Cracks at Base of BMV.

Step 2 – SEM (+EDX).
Surface investigation at the point of interest.
Chemical etching can yield additional data regarding basic crystal structures.
Electro polishing may yield outline of layered structures but is not always conclusive.
"Macro" elemental analysis.

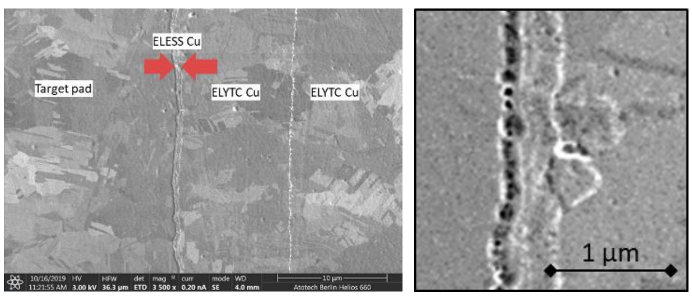

Figure 14. SEM Images of Electro Polished Sample.

Step 3 – SEM-FIB (+EDX).
Inspection normal to the point of interest.
Determine crystal structures and any breaks in epitaxy across the target pad – plated Cu interface.
Approximate locations of layers may be possible.
"Macro" elemental analysis. Caution should be taken when inspecting open cracks as redeposition can occur during milling operations.

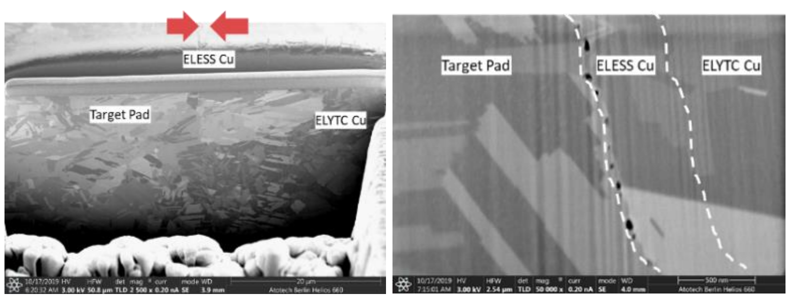

Figure 15. SEM-FIB Images Showing Crystal Structure.

Step 4 – TEM (+EDX).
Inspection of nano scale features
"Micro" elemental analysis of the point of interest
Confirm location of ELESS Cu
Identification of trace impurities

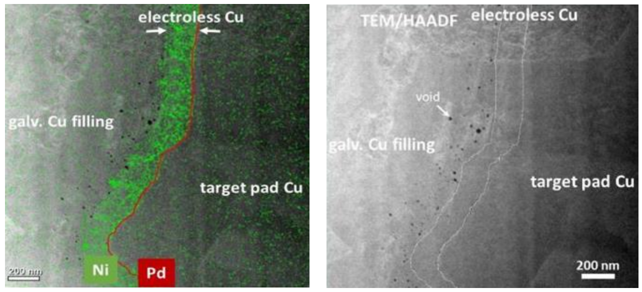

Figure 16. TEM Images Showing Elemental Analysis and Nano Voids.

Summary.
There is an increasing awareness and concern regarding the reliability performance of stacked microvia in advanced PCBs leading to extensive works investigating BMV failure. Through a number of associated investigations, it has become apparent that the use of SEM-FIB has become popular as it offers an enhanced understanding of the complex crystallography present within the microstructures of a plated and filled BMV. Care should be taken however when utilizing SEM-FIB as there is a risk of preparation artifacts which can impact the conclusions drawn, as such, and based on our own experiences, a recommended best practice for the investigations of failed BMV is offered.

References
[1] – *Magera J. et al.* IPC-WP-023 "IPC Technology Solutions White Paper on Performance-Based Printed Board OEM Acceptance. Via Chain Continuity Reflow Test: The Hidden Reliability Threat — Weak Microvia Interface. (May 2018)
[2] – *Magera J*. Strickland J.R "Copper Filled Microvias – The New Hidden Threat". Proceedings of IPC Apex EXPO (2019)
[3] - *Bernhard T., Gregoriades L., Branagan S, Stamp L., Steinhäuser E., Schulz R., Brüning F*. "Nanovoid Formation at Cu/Cu/Cu Interconnections of Blind Microvias: A Field Study" IMAPS International Symposium on Microelectronics Proceedings (2019)
[4] - *Bernhard T. Branagan S.*, "The formation of nano voids in electroless Cu layers", MRS Spring conference (2019), submitted to MRS Advances (2019)
[5] – Zarwell. S, Bernhard. T. *Steinhäuser E., Kempa. S. Brüning F*. "The Effect of Cu Target Pad Roughness on the Growth Mode and Void Formation in Electroless Cu Films" IWLPC Proceedings (2019)