Relevance of 3D x-ray imaging for electronic packages and printed circuit boards

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ABSTRACT

X-ray inspection systems are key tools for quality control, yield enhancement and failure analysis of PCBs and semiconductor devices for over two decades. In many cases, these capable tools provide the only non-destructive techniques for inspection of electronic components. There have been significant improvements in the X-ray inspection capabilities (both 2D and 3D) in the last several years. Applications such as artificial intelligence (AI), 5G, high-performance computing and internet-of-things (IOT) mandate higher IO density and 3D scaling at the device, package and system levels, thereby increasing the need for non-destructive imaging at high resolution and preferably in 3D. In this paper, we discussed a nondestructive approach for printed circuit board (PCB) by using real time x-ray imaging system under 3D mode. We demonstrate our proposed process on PCB, a six-layer custom designed board and few more complex commercial boards.

1. Introduction

Modern semiconductor packages are constantly increasing in complexity and functional density. Just like for IC technology nodes, these demands lead to shrinking feature sizes, novel material introduction and interactions. As a result of this trend, physical failure analysis of package-related defect mechanisms is growing in both urgency and importance, and therefore requires new types of sample preparation and measurement techniques. One of these new techniques is 3D X-ray or X-ray tomography which has been introduced and widely adapted in the past years for non-destructive testing [1].

Packaging of integrated circuits is growing more and more complex, and housing multiple dice in a single package is just another challenge chip maker face. Typically, these dice are connected in complex ways, and chipmakers must contend with shrinking feature sizes and interconnects, escalating device density and package size, thinner layers, and a widening variety of materials. Visualization of defects aids determination of the root cause. Packages are essentially opaque boxes containing electrical connections which can be visualized through a Non-Destructive Technique (NDT) like X-ray imaging. Maintaining integrity of the defect site is critical. If a sample is cut or reduced in size, further electrical analysis may not be possible, and the structure may be disrupted by introducing artifacts or changing the stress profile from that of an intact sample. Conventional non-destructive methods have become less effective at visualizing defects in many of today's packages, creating a significant need for new non-destructive approaches such as 3D X-ray imaging system. The Real Time X-ray Imaging is extensively used for nondestructive testing of electronic components to inspect wire bonds, die attachments, lid seals, foreign particles inside the hermetically sealed packages etc. Multi-layer PCBs could also be inspected to find any process imperfection between adjacent layers [2].

Multilayered Printed Circuit Boards (PCB) dominate most of the electronic equipment in use today. The multilayered architecture has allowed the top and bottom surfaces of the PCB to be used primarily for component mounting with the majority of tracks on the internal layers. The complexity of the PCB depends on the fabrication process with some manufacturers producing PCBs up to 35 layers. Feature size has

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also been reduced, with signal tracks approaching 25µm wide and vias small enough to be completely obscured by even the smallest of surface mount components. This has led to more compact, densely populated complex PCBs that present a challenge for any testing or fault analysis. The X-ray source/detector rotates around the object producing a dataset of 2D X-ray slices. This dataset can then be reconstructed into a full three-dimensional (3D) image of the object including any internal layers of a PCB.

In this study, we introduce high-resolution 3D X-ray imaging technique into the daily failure analysis (FA) work flow for semiconductor packages. Two application cases, viz., verification/ inspection of metallization defects in multilayer PCBs and inspection of balls & solder joints of BGA (Ball Grid Array) packages have been selected to demonstrate its advantage that could be made in the overall quality and reliability of the product.

2. Principle of Real-Time X-Ray System with 3D Imaging Capability

Real Time X-ray imaging is as simple as mounting the sample on five axis manipulator and adjusting for the optimum viewing angle. The power level is continuously adjustable from 30kV to 160kV and up to 1mA for penetration of a wide range of samples. The signal to noise ratio could be adjusted according to get a better picture on the screen. The contrast of the image could be improved by integrating, sharpening and filtering the image. Here, we used a Nordson DAGE XD7600NT Ruby X-ray Inspection System. This particular system had Nordson DAGE's X-Plane software installed, which provided the 3D imaging capability. Typical Specification of a real time X-ray system is given in Table-1.

A 3D X-ray imaging system consists of an X-ray source, stage and rotating X-ray detector. The X-ray system constructs the 3D volume of the sample by capturing a series of 2D X-ray images at different angles. All the 2D images are then mathematically processed and superimposed to construct the 3D volume of the sample, which process is known as reconstruction. These X-ray images allow inspection of the sample at a certain location to be done easily and it is also possible to display a cross-section or slice view of the sample. The space between the X-ray source, sample and detector is a critical parameter because it determines the magnification and resolution of the X-ray image.

Table 1
Typical specification of a real-time X-ray system.

Sl. No.	Technical Points	Required Specification
1	Tube Voltage (Range)	Continuously variable Voltage: 30kV to 160 kV or higher range
2	Electron beam power (Tube Power)	≤10W
3	Target	Long Life Diamond Target
4	Geometric magnification	2000X
5	Feature recognition (Resolution)	0.5µm
6	Sample movement	5 Axis movement (X, Y, Z and 360^{o} rotation and 60^{o} inclination
7	Maximum Inspection Area	400mm x 350mm or more
8	Maximum Sample size (area wise)	600mm x 450mm or more
9	Image detector	CMOS digital detector with 1600 x 1200 pixels resolution
10	Software	• Capable of viewing individual 2D slices within a sample from top-to-bottom and at any plane in between. • Capable of 3D reconstruction of the image without cutting the board
11	Post processing of image (Software features)	• Automated and manual calculation of attachment/ interconnection voids. • X-Ray navigation map for easy fault location.

3. Results and Discussions

This section demonstrates the capabilities of the real time X-ray imaging system by describing certain chosen case histories. X-ray inspection equipment is typically used during the PCB assembly process to verify component placement and proper solder quality, or after the assembly process for failure analysis to identify, locate, or troubleshoot defective features. X-rays emitted from an X-ray tube on one side of the target object and captured by a detector on the opposite side. X-ray inspection can still be useful to some extent, as one can get a general sense of PCB construction/layout and, for simple boards, visually follow traces/connections by manipulating the X-ray's angle and field-of-view in real time.

Computerized Tomography (CT) is an X-ray imaging method where a series of 2D X-ray images are post-processed to create cross-sectional slices of the target object. CT is frequently employed for complex inspection and failure analysis of PCBs, electronic component packaging, and solder ball quality. For our experiment, we used a Nordson DAGE XD7600NT Ruby X-ray Inspection System. This particular system had Nordson DAGE's X-Plane software package installed, which provided the CT functionality. The goal of this phase is to obtain images of individual layers of multi-layer PCB using nondestructive imaging techniques. Such techniques may be successful even against a fully assembled/populated PCB.

The first step in the process was to capture a series of 2D X-ray images (between 60 and 720, depending on the desired resolution of the resulting cross-sectional slices) by rotating the X-ray 360° in a single axis around the target object. In our case, 360 images were taken around a multilayer-layer PCB at 45° inclination angle. Next, mathematical post-processing of the images resulted in 240 2D slices that could be viewed in any plane (X, Y, or Z). These slices were then imported into the analysis software (in this case VG Studio), which provided a graphical environment to analyse the images and to add various effects to show depth or highlight specific areas.

3.1. Inspection of populated PCB

A 6-layer PCB had components mounted on its both sides (top & bottom). During electrical testing, it was identified that IC U13 was not functioning properly. IC U13 was mounted on top side, and another IC of the same type was mounted just below U13 on bottom side, which is clearly observed in xray image (Fig.1). Due to the nature of 2D X-ray imaging, the resulting images were composites of all PCB layers. This made it difficult to determine on which layer a particular trace was located.

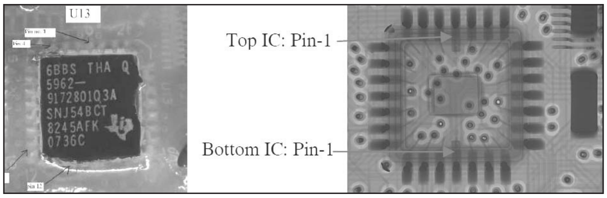

Fig. 1. IC mounted on a 6-layer PCB (left) and its 2D x-ray image (right) showing two ICs mounted back-to-back on top and bottom layer of the PCB.

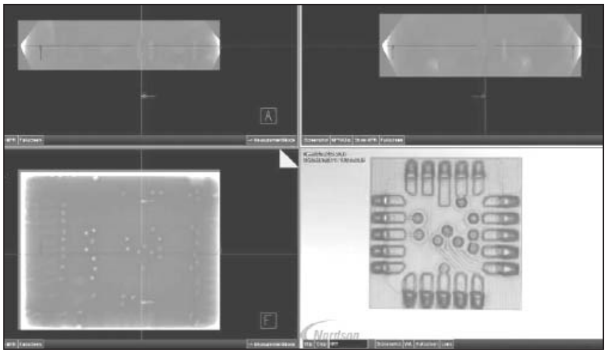

Fig. 2. 3D X-ray image analysis depicting clearly the top layer of the PCB.

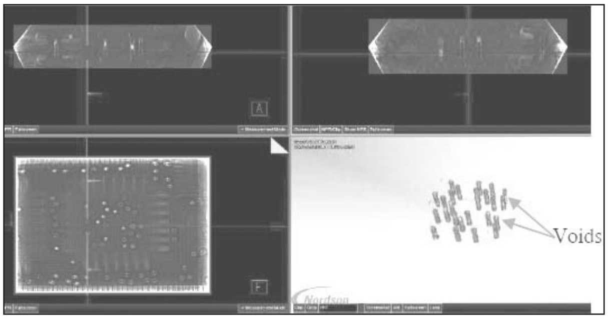

Fig. 3. 3D X-ray image analysis depicting voids or insufficient filling in the vias of the PCB.

3D x-ray imaging will help us in inspecting each layer individually by separating different layers. As described earlier, 3D x-ray scanning was performed and the reconstructed 3D x-ray images were analyzed for layer-by-layer inspection. Fig.2 depicts the top layers of inspected PCB. It may be noted that image of top layer of the PCB is free from any over-lapping or super imposition of images of other layers of the PCB and mounted components. The PCB vias connecting different layers of the PCB are predominantly

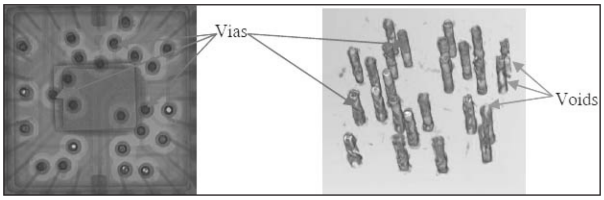

Fig. 4. Vias in the PCB as observed in 2D X-ray image (left) and 3D X-ray image (right).

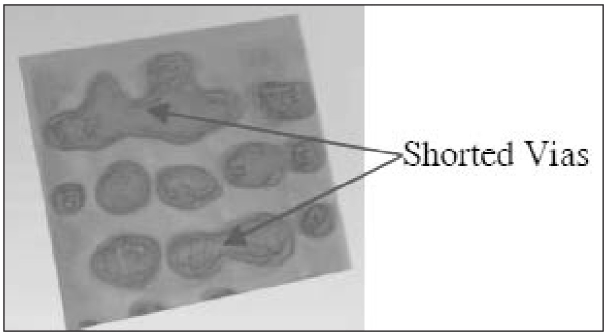

Fig. 5. 3D X-ray analysis revealed shorted vias in an inner metal layer.

illustrated in Fig.3, which shows the defects in vias as voids or insufficient filling. In contrast to 3D x-ray analysis, no clear voids or insufficient filling within vias were observed in 2D x-ray inspection (Fig.4). The observed voids reduce the effective cross-section of vias, and thereby increase current density in vias. The increased current density may give rise to electro-migration (EM) related failure.

The layer-by-layer inspection of the 3D x-ray images were carried out carefully to look for any defects in metal layers. It was found that the neighbouring vias were shorted in an inner metal layer (Fig.5). It could not be detected in 2D x-ray imaging due to overlapping and superimposition of images from various layers and components.

3.2. Inspection of BGA solder joints of assembled PCB

High speed digital circuits and high-density packaging of electronic industry has been achieved using BGA and CGA IC packaging. The sold joints of BGA balls or CGA columns with PCB are not accessible for optical inspection. Normal x-ray (2D) is not successful either to detect the defects on solder joints of ball/column as discussed earlier. However, 3D X-ray analysis allows us to inspect solder joints of ball/ column by combing the layer-by-layer view with image contrast and enhancement effects. Fig.6 illustrates the solder joints of the BGA ICs inspected with 3D x-ray analysis, which revealed voids in solder joints of balls with PCB. The observed voids may affect the mechanical as well as electrical performance of the circuits depending upon the extent of voids.

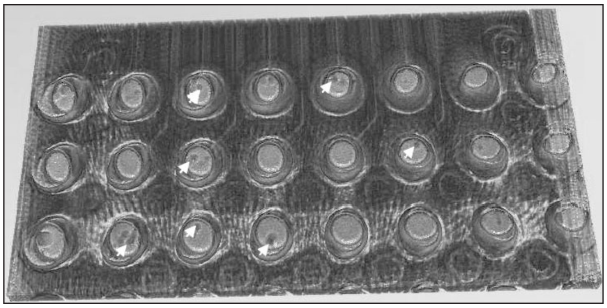

Fig. 6. 3D X-ray analysis revealing voids (marked with arrows) at solder joints of balls.

Although the improved X-ray inspection methods is promising to inspect micro voids in solder joints and track shorts buried inside, the limitation related to resolution of detecting smaller defects is still challenging. Also, the success of 3D X-ray analysis may vary depending on PCB construction features, such as layer stack-up, material composition, copper weight, and component placement.

4. Conclusion

An advanced real time radiographic capability has been demonstrated for effective nondestructive evaluation of components and assemblies. Critical evidences like shorts and voids in metal tracks/vias and solder joints in populated/ wired PCB could be obtained using real time x-ray system. This paper detailed our PCB deconstruction experiments, including solder mask removal, delayering, and imaging, and provided a number of practical, effective techniques that could be used to access individual layers of a target circuit board. It is hoped that our work will serve as a comprehensive guide to PCB deconstruction techniques and help those involved in electronic product development understand.

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6. References

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