

# Modern 2D / 3D X-ray Inspection - Emphasis on BGA, QFN, 3D Packages, and Counterfeit Components

By Evstatin Krastev and David Bernard

## Abstract

With PCB complexity and density increasing and also wider use of 3D devices, tougher requirements are now imposed on device inspection both during original manufacture and at their subsequent processing onto printed circuit boards. More complicated and dense packages have more opportunities to exhibit defects both internal to the package as well as to the PCB. As components increase in complexity their cost increases, making counterfeiting them a potentially lucrative business for unscrupulous individuals and organizations.

Recent years have brought significant improvement in the capabilities in the 2D/3D X-Ray Inspection systems. New X-ray sources, detectors, and ergonomic features improve the efficiency and productivity of the inspection process.

This paper reviews the methods of finding defects in BGAs, QFNs, and 3D packages using X-Ray inspection with real-life examples provided. Voiding, cracks, shorts, open joints, and head in pillow (HIP) will be discussed. Comparison of the relative merits of the 2D and 3D (CT) X-Ray inspection for investigating 3D packages is presented with examples. Using X-Ray inspection for detecting counterfeits is discussed at the end.

Key words: BGA, QFN, X-ray inspection, Computer Tomography, CT, 3D packages, POP, PIP, SIP, stacked die, defect

## Introduction

Traditionally, the use of 2D x-ray inspection provides important and at the same time a non-destructive method for investigating all aspects of device production and subsequent PCB assembly. In recent years increased use of area array packages like BGAs and QFNs, CSPs and flip chips makes traditional optical methods of inspection ineffective as the joints to the PCB are hidden under the package. In order to use optical means to inspect the above cases the device needs to be physically removed prior to inspection, which practically destroys the assembly. In addition, during the process of physically removing the device, vital information can be lost or additional defects introduced. X-Ray inspection is also used to inspect the wire and die attach quality inside the individual package without opening the package. This technique is very handy for detecting counterfeit components while keeping the parts in their sealed, as-received packaging.

With increasing system integration, new 3D packages like package in package (PiP) and package-on-package (PoP) are replacing standard leadframe packages. These new packages incorporate multiple dies stacked on the top of each other, multi-level wire bonding and interconnection. The ultimate goal is to achieve greater circuit density resulting in better overall performance of the assembly. These new and more complex devices are bringing their own requirements and

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challenges to the inspection and quality control process during device assembly, test and subsequent assembly onto printed circuit boards. In some cases this increased complexity requires the use of 3D Computer Tomography (CT) technique in addition to the traditional 2D oblique angle X-Ray inspection. This is facilitated by the fast and straightforward switch between 2D and 3D CT inspection mode offered by the modern X-Ray system. Practically the range of applications of the modern X-Ray system is very large with the electronics inspection being one of the main groups. X-Ray is also a useful tool for inspecting medical, other mechanical and optical devices.

## Basics of an X-ray System

The 2D X-Ray inspection systems are essentially X-Ray microscopes (Figure 1 and Figure 2). A wide cone of X-rays is emitted by the source (X-Ray tube). The inspection is accomplished by moving the sample inside the X-Ray emission cone. All materials absorb the X-Ray radiation differently depending on their density, atomic number and thickness.

Thicker and/or denser material will absorb more of the X-Rays. The resulting image, composed of shades of grey with darker areas corresponding to higher X-Ray absorption, is registered by the X-Ray imaging device, usually a very high quality digital image intensifier or a flat panel. The closer the sample is to the X-Ray source the higher the magnification level (Figure 1). The ability to inspect at an oblique angle view is crucial for finding defects like cracks and open joints. Generally two ways are used to accomplish oblique, or angled views - tilt the sample or tilt the imaging device. As seen in Figure 2, tilting the imaging device has the huge advantage of producing maximum magnification at all tilt angles.

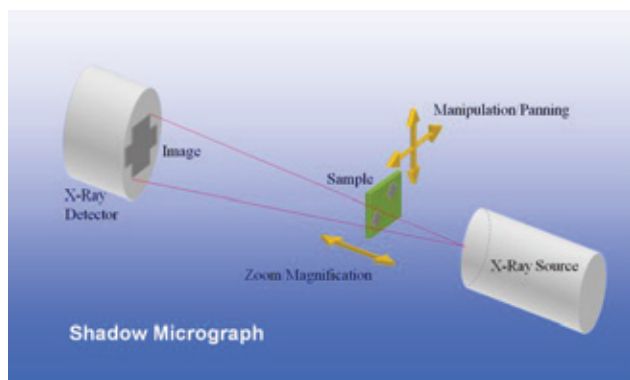


Figure 1. Basic operation principle of X-Ray inspection system

The modern X-Ray machine tilts the imaging device up to 70 degrees at the same time permitting images from 360 degrees around any inspection point. A sophisticated combination of software and hardware keeps the point of interest (for instance a defective joint) in the center of the field of view while the imaging device is rotating around and examining from all directions. Additional advantages of this method are that there is no need to secure the sample (PCB, component or another device) and no risk of dropping, damage or collision during sample manipulation.

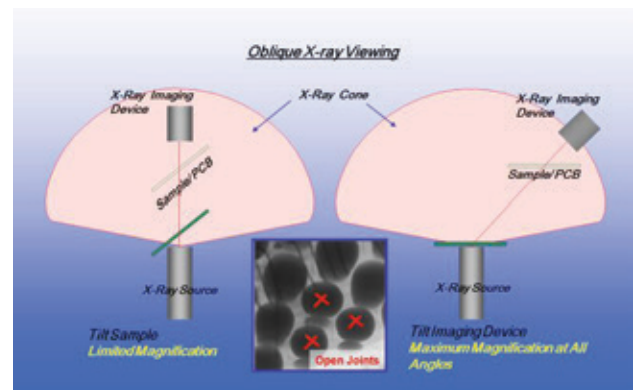


Figure 2. Oblique angle viewing

During the last several years, X-ray source and digital detector technology have significantly developed. Submicron feature recognition as fine as 100 nanometres (0.1 micron) is achievable in 2D mode as well as system magnification levels of 12,000X. These advancements allow inspection of finer detail and a corresponding increase in the detection of potential defects. Sealed transmissive, filament-free X-ray tube technology combines the highest performance levels with maintenance-free or minimal-maintenance operation, which reduces downtime in an active production environment.

The latest imaging systems provide real-time digital inspection at 2.0 mega-pixels, 30 frames per second and 65,000 greyscale levels, viewed on 24" ultra-high-definition LCD monitors. The important point here is that these advancements in image quality and enhanced feature recognition make the inspection process much faster, more effective, and highly reliable.

## 3D Computerized Tomography (CT)

Computerized Tomography (CT) is an X-Ray imaging method where mathematical geometric processing is used to generate a 3D virtual model of an object from a large series of individual 2-D X-Ray images taken as the object is rotated through 360 degrees in the x-ray beam.

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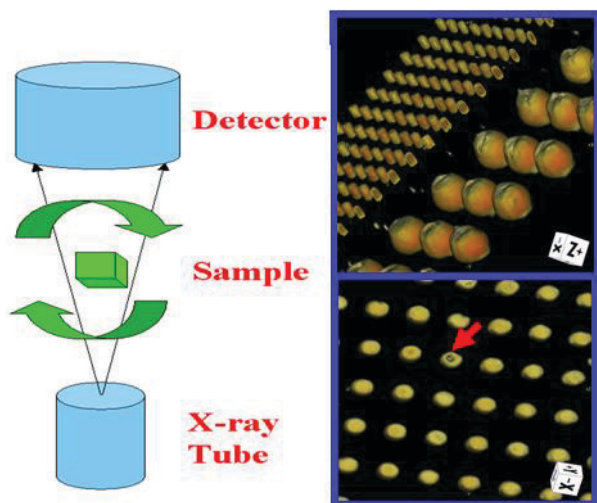


Figure 3. Typical layout of a CT system and an example of a CT model

The layout of a CT system is shown in Figure 3. Once the CT model has been produced, it enables 'virtual micro-sectioning' by allowing the operator to investigate any two-dimensional plane within the entire model as well as full, real time manipulation of the 3D model. In this way, different layers and different features within the package can be viewed whilst being isolated from other, potentially confusing, detail to enable improved analysis. This allows complete examination of features or defects within a device or package that would otherwise remain hidden by multi-level interconnections. For example, the tiny 100-micron solder bumps within the multi-layered device shown on Figure 3 would be obscured by the much larger 500-micron BGA balls.

The modern 2D/3D X-Ray inspection system can be switched from 2D to 3D CT mode in a couple of minutes, facilitating the joint use of the two techniques providing powerful and non-destructive analytical capabilities.

## Defects in BGA and QFN Packages

Common BGA defects like voiding, shorts, cracks, and head-in-pillow (HIP) or head-on-pillow (HOP) usually occur during reflow. The oblique angle capability is critical for detecting cracks and HOP defects using viewing angles of 55 to 70 degrees. Voids and shorts are easily visible using a top-down view, but in order to determine the location of the voids oblique angle 2D viewing and 3D CT come very handy. The angled view on Figure 4 reveals voiding concentrated on the joint interface making the particular connection less reliable and possibly more prone to failure in the field.

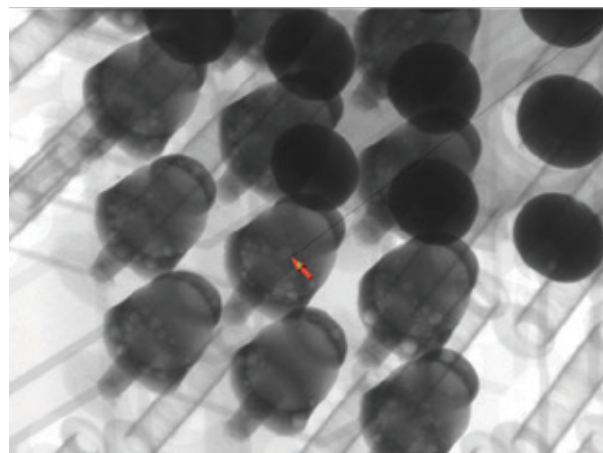


Figure 4. Angled/ oblique 2D X-Ray view showing interface voiding

The 3D CT technique permits virtual slicing or cross-sectioning through the devices revealing the exact location of the voids as seen on Figure 5.

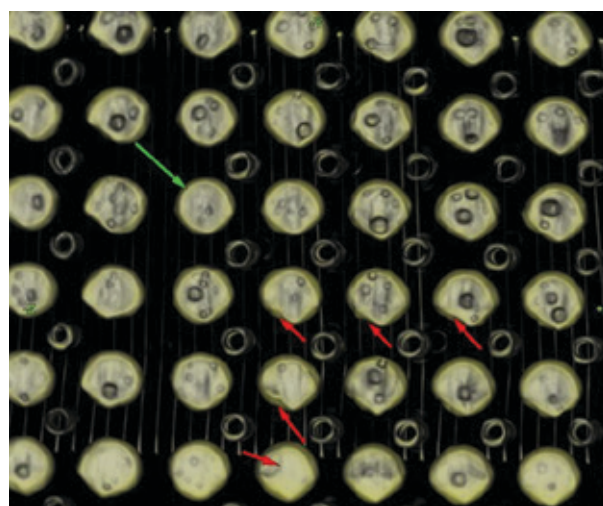


Figure 5. CT virtual section through the interface region of a BGA device.

Large amount of interfacial voiding is apparent and many BGA balls marked with red arrows are deformed/ cracked. The modern 2DX machine features automatic routines designed for precise measurement of diameter, voiding percentage, shape and area of the BGA balls. As seen in Figure 6, the BGA balls marked in red outline fail the requirement for shape or roundness, which is the first number accompanying each ball. The second number represents the total voiding percentage for each BGA ball. It is up to the operator to set up the acceptable levels and the machine will automatically flag any values which fall outside.

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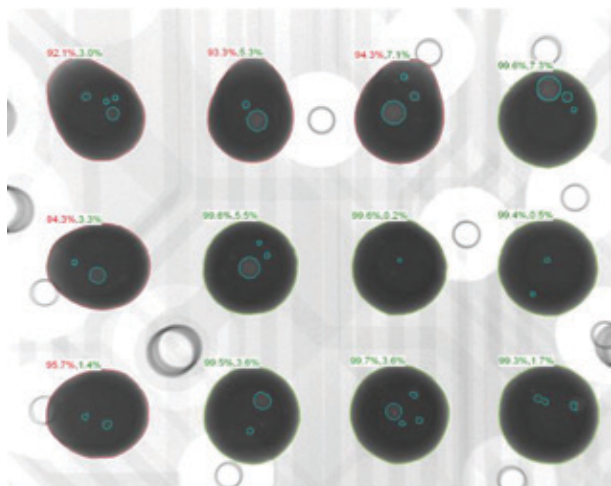


Figure 6. 2D X-Ray voiding and roundness calculation for a BGA device.

Head-in-pillow (HIP) defects, also known as head-on-pillow (HOP), occur during reflow. The solder paste wets the printed circuit board pad while not fully wetting the BGA ball.

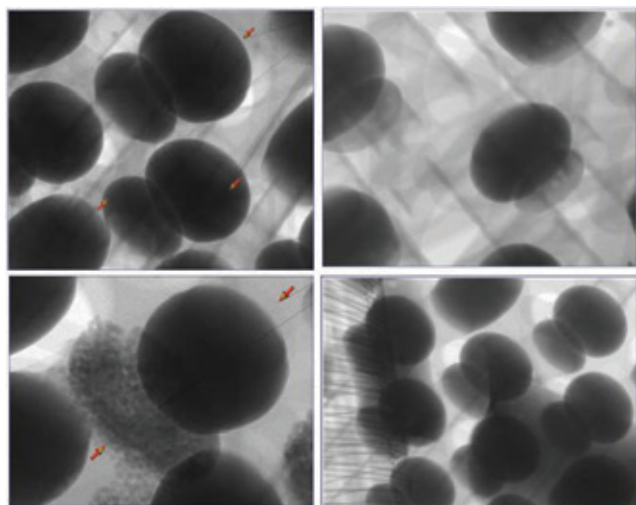


Figure 7. Various examples of HOP defects easily identifiable with off-axis 2D X-Ray inspection

Even though the HOP joint might at first exhibit electrical conductivity it lacks mechanical strength and fails in the field. In many cases the BGA device incorporating HOP defects is not functional from the very beginning. The HOP defects have become more widespread with the arrival of lead-free solder paste due to greater board warpage and solder ball lifting caused by higher reflow temperatures. Process variables impacting HOP defects include solder ball alloys, the type of reflow profile, peak reflow temperature and solder paste chemistry.

Even though HOP defects can be difficult to detect when using in-line automatic X-ray inspection (AXI) systems or lower performance 2D systems, they can be quickly and easily identified using modern high-performance 2D X-ray system with an oblique angle viewing (Figure 7). In addition the inspection process is completely non-destructive.

The only other practical way of confirming HOP defect residing in the middle of a BGA is by cross-section and scanning electron microscope (SEM) or optical examination; however this method is destructive resulting in damaged and unusable PCB and BGA component.

Figure 7 shows various examples of HOP defects. It is obvious why these defects are referred to as head-in-pillow, or better head-on-pillow. The defective BGA solder ball appears to be laying on the reflowed solder paste instead of forming a single joint after reflow. Figure 8 is a virtual CT micro-section through the BGA device revealing a 3D view of the HOP defect.

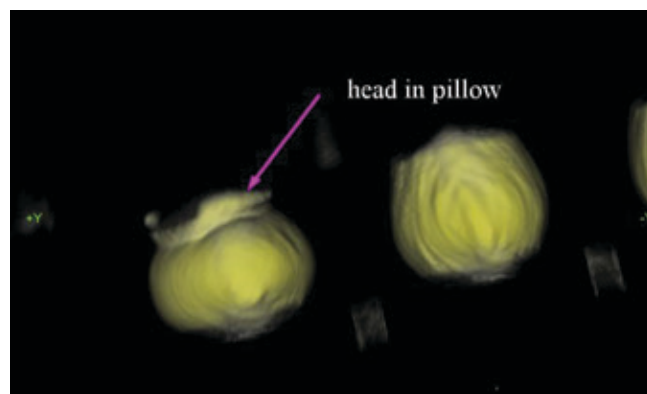


Figure 8. 3D CT section showing HOP defect in a BGA device

The traditional method for detecting HOP defects is manual inspection at an oblique angle of 55 to 70 degrees performed by the operator. This method, although being very reliable, is time consuming and labor intensive. As a further step, an automatic HOP inspection routine has been developed that can identify suspect HOP defects without requiring an operator to manually inspect each individual solder joint location within a BGA. The routine scans the entire BGA device; a sophisticated artificial intelligence algorithm analyses all BGA solder balls and highlights the ones considered to be HOP defects to the operator by displaying a color coded overlay on-screen. This is a very important development providing additional confidence in solder joint integrity and helping to prevent HOP defect escapes.

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The Quad Flat Pack No Leads (QFN) style of leadless package is also becoming more and more popular because of its low cost, low profile and excellent electrical and thermal parameters. It is widely used in the wireless, automotive telecom and many other applications because of the merits outlined above. Although most commonly known as QFNs, the same, or similar, package types are also known under other names. The most common alternative is Land Grid Array (LGA).

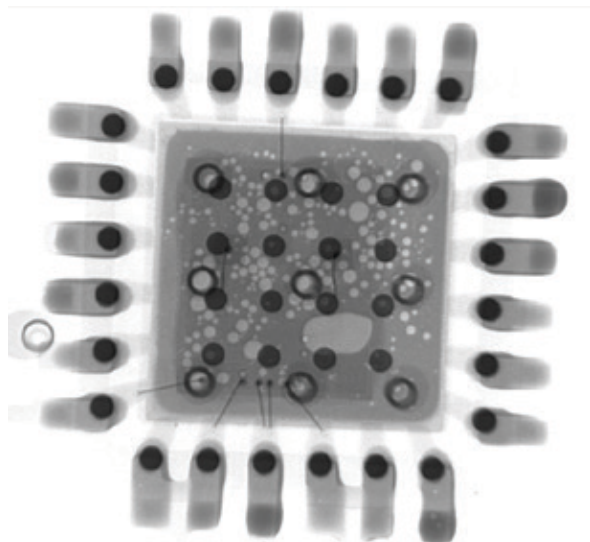


Figure 9. Top X-Ray view of QFN package

As shown on Figure 9, the package terminations are all located under the device. This makes the traditional Automatic Optical Inspection not practical. As with the BGA devices, cross section followed by SEM or optical evaluation is an alternative, but the method is destructive and permanently damages the device and PCB.

Modern 2D X-Ray systems provide a fast, effective and non-destructive method for inspecting QFNs. A relatively inexperienced operator can quickly assess and quantify the analysis within the production environment. With a lesser X-Ray inspection system that lacks good magnification, resolution, contrast sensitivity, and high angle oblique viewing the analysis could be less straightforward and reliable.

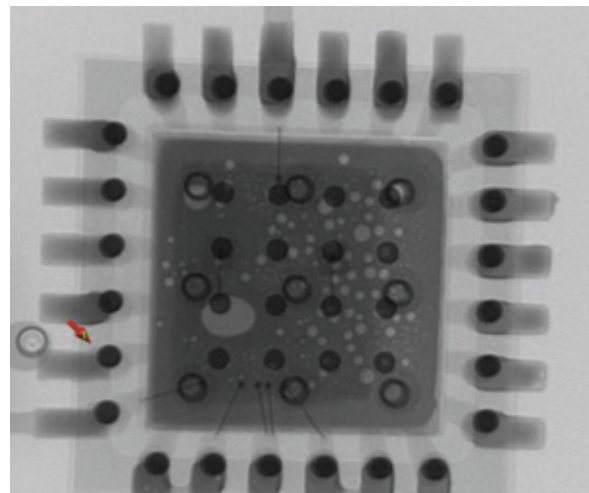


Figure 10. Top X-Ray view of LGA package.  
Suspected pin pointed by arrow.

Figure 10 shows a low magnification image of a QFN package with a red arrow pointing out to a suspect pin. Because of the high resolution and contrast sensitivity of the X-Ray system, a possible defect is apparent even at this low magnification image.

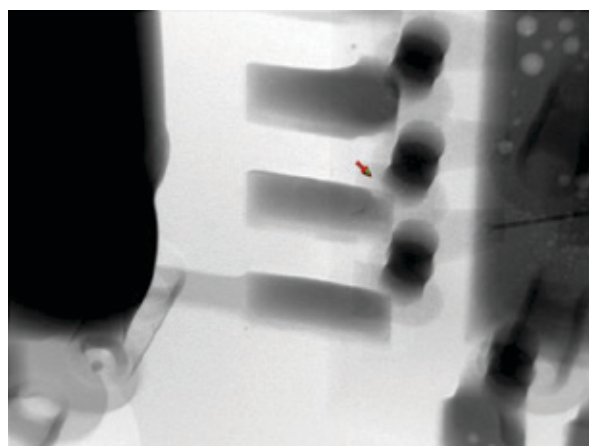


Figure 11. Higher magnification oblique angle view of defective pins from Figure 10.

Using oblique view and higher magnification one can study the open pins in detail as shown in Figure 11. However, even a low magnification oblique view is sufficient to confirm the defect as seen in Figure 12.

The fact that the defective pins can be identified at such low magnification levels makes the X-Ray inspection process fast, efficient and reliable. Figure 13 represents an oblique angle 2D X-ray view of different QFN device. The red arrows are pointing towards open pins compared to the good pins (green arrows).

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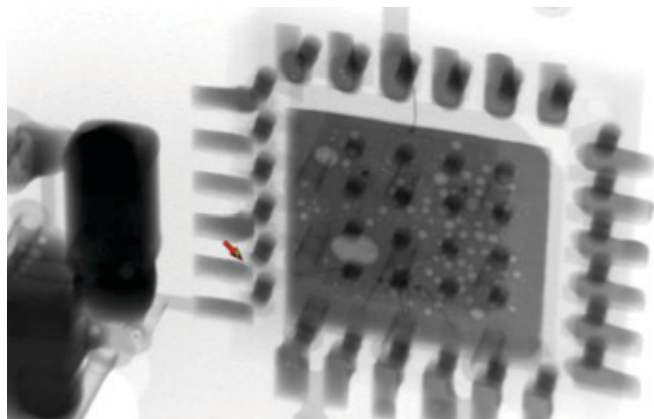


Figure 12. Low magnification oblique X-Ray image showing defective (open) pins in QFN device.

It is important to point out that in addition to the quality of the side connection, the voiding within the central large pad is also crucial in some cases when large amounts of heat need to be transferred out of the device in order to prevent overheating. The example (Figure 9) shows significant voiding in the central area which would be a concern or reason for rejection in a high-power application.

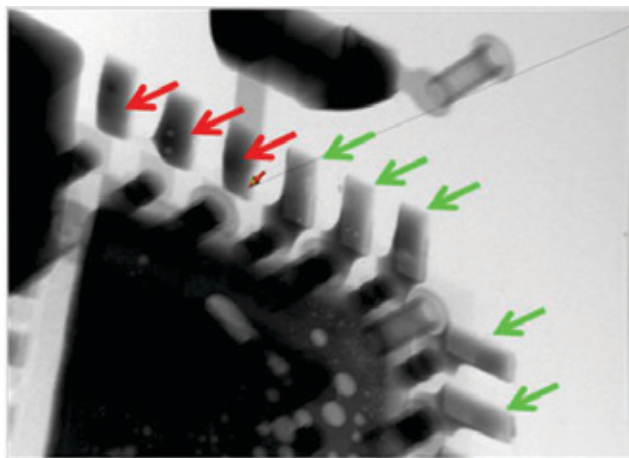


Figure 13. Oblique 2D X-Ray view of defective QFN device. Red arrows point toward open pins and the green arrows identify good pins.

## 3D Packages

With the continuing trend for subsystem integration, advanced 3D packages including PiP, PoP, SiP and flip-chip devices are replacing standard lead-frame packages. Many of these exotic packages meet the demand for greater circuit density and improved electrical performance, however the increased complexity generates unique challenges for the inspection and quality control process during device packaging and subsequent

assembly. Traditionally, the use of 2D X-ray inspection provides a vital and non-destructive method for investigating all aspects of device production and PCB processing. However, with 3D package investigation, 2D X-ray imaging may be limited since all layers within the device are seen at the same time, projected on a plane. Analytically, this can be confusing to the operator because the multiple dies and multiple layers of wire bonds will appear to overlap each other in the x-ray image.

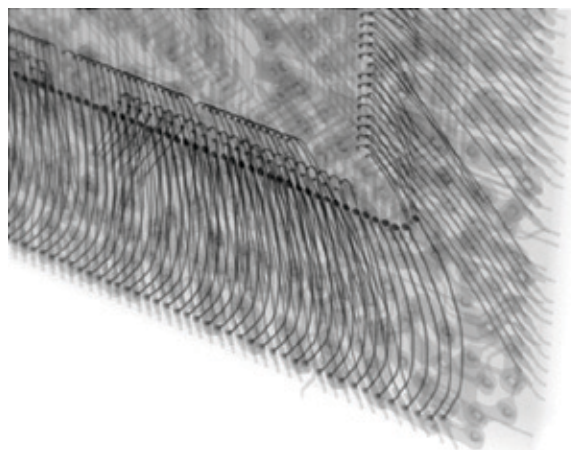


Figure 14. 2D X-ray oblique view of stacked device.

As seen on the 2D X-Ray image in Figure 14, the two wire bonding layers of this stacked device cannot be easily separated for analysis looking for shorted or open connections.

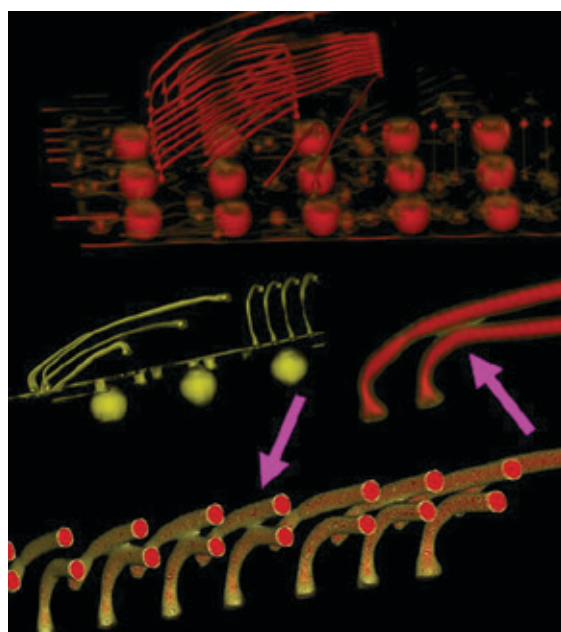


Figure 15. CT images of stacked devices showing shorted bond wires.

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Figure 15 is a combination of CT images showing various stacked devices. The CT technique permits the operator to isolate the area of interest and carefully examine for potential failures using virtual micro-sectioning. As seen on Figure 15 the shorted wires are easily identified using CT and this cannot be easily and reliably accomplished using 2D methods.

Another example of the powerful CT technique is shown in Figures 16 and 17.

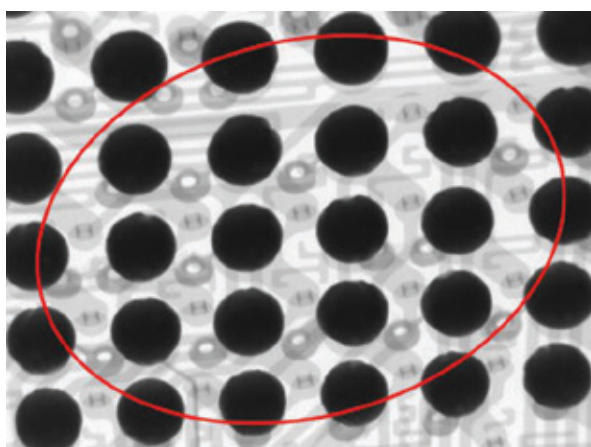


Figure 16. 2D X-Ray image of an area containing suspect shorted vias in a 3D package

The examined 3D device has shorted vias in the region covered by the 2D X-Ray image on Figure 16. Clearly identifying the defect is quite difficult due to the complexity of the 2D X-Ray image. The CT model of the same package is shown on Figure 17. The CT model is also quite complicated, but once the micro-sectioning capability is engaged the shorted vias pop up easily detected -- see inset of Figure 17 representing a virtual micro-section through the CT model.

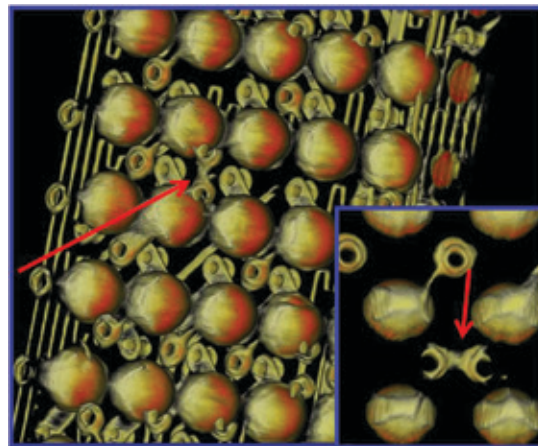


Figure 17. CT model of the 3D device shown on Figure 16. The inset is a virtual cross-section easily detecting the two shorted vias.

## Counterfeit Components

The problem of counterfeit components penetrating the supply chain has been growing during recent years, with most board assemblers admitting to having received some recently, costing them prestige and lost money. Low cost (less than \$10 apiece) counterfeits tend to be devastating as it is hard to justify thorough extra tests, while counterfeiters make it even more difficult by providing some good samples at the end of the reel.

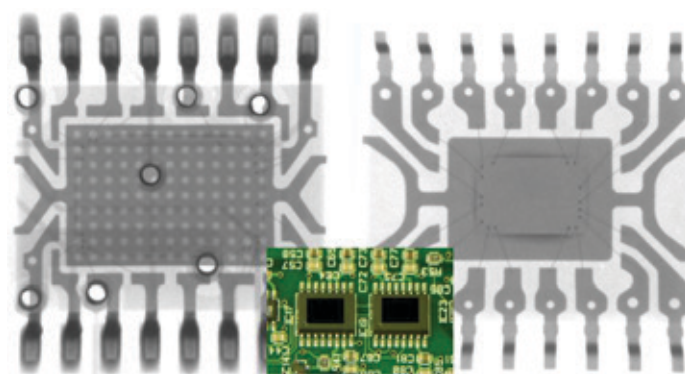


Figure 18. 2D X-Ray image revealing big differences between components looking similar optically, thus easily identifying the counterfeit.

As shown in Figure 18, the real and fake components might look very similar optically, but an X-Ray image reveals big differences. The modern 2D X-Ray inspection provides a fast and effective method to identify counterfeit components. Being non-destructive and offering high magnification, resolution and contrast sensitivity it makes it easy and straightforward for the operator to identify the fake components by observing die placement, internal wiring and comparing to known good samples.

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## Conclusions

Modern 2D/3D X-Ray inspection systems are powerful tools for finding defects in BGA, QFN and 3D packages and also provide fast and straightforward method for identifying counterfeit components. During the last several years, significant advancements in the X-Ray technology including sealed-transmissive X-Ray sources, extremely high quality digital imaging intensifiers, and ergonomic features, has brought the X-Ray inspection to a new and much more advanced level, making the X-Ray inspection much more effective, faster and reliable.

### ACKNOWLEDGMENT

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