µCT For 3D Analysis Of Complex Assemblies

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With current and future advances in semiconductor packaging technology, a significant move from 2D to 3D X-ray inspection has to be expected to account for continued miniaturisation and expansion into the third dimension. Applications ranges from packaging analysis with the full assessment of wire bond alignment to solder integrity between stacked dies. Continuous growth in electric and electro-mechanical system complexity with increasing exploration of all three dimensions drive the need for 3D Microfocus computed tomography (µCT). Technological advances addressing major shortfalls of conventional time-consuming µCT inspections have reduced µCT inspection times from hours down to a couple of minutes.

With the increasing demand for more functional and smaller sized portable devices such as cell phones, mp3 players, and GPS units, the performance and size of individual electronic components have become critical. Engineering a single package with multiple chips stacked vertically one on top of the other results in the combined computing power of the two individual integrated processors, yet will have smaller and more efficient packaging of devices. Escalating from 2D single die designs to 3D multiple die package solutions, the typical inspection tools are no longer sufficient. While Microfocus 2D X-ray has been the traditional inspection tool to verify wire bond, die attach and flip chip integrity, when there are multiple layers of interconnects, the resulting 2D image from an X-ray microscope is often too intricate to analyze effectively. These complex assemblies drive the need to simplify inspection by virtually cross-sectioning a sample. By separating each layer into individual sections, die attach voids, wire bond integrity and solder interconnects can be easily viewed. Micro-Computed tomography (µCT) has become the preferred method for 3-dimensional analysis of complex electronic assemblies and can simplify the inspection process of stacked die components.

Drivers for stacked components

3D packaging is the general term that encompasses stacked components, 3D IC's, Package-on-Package, System-in-Package, System-in-a-Cube and many others. The primary driver of 3D Packaging is that the technology saves space by combining separate chips in a single package. Traditionally a 3D package contains two or more layers of active electronic components, stacked and integrated vertically and horizontally in a single package. The components communicate as if they were mounted in separate packages. The methods of communicating from die to die and from die to package are the similar to those used with a single die package.

Figure 1 – Stacked die

Applications

Portable products such as cell phones, digital cameras, PDAs, audio players and mobile gaming devices demand higher memory capacity, yet need to maintain innovative packages and styling. Memory requirements for increased storage space and I/O speed promote strong growth in the transition from single-die to 3D packages and from wire bond to flip chip interconnections. Ultra-small memory cards with large storage capacity have been developed using 3D packages to meet the demand.

Additionally, a desire to include multiple multi-media functions in smaller products such as phones with integrated video and audio players, higher resolution cameras, and support of multiple RF signals, requires more I/O in the same

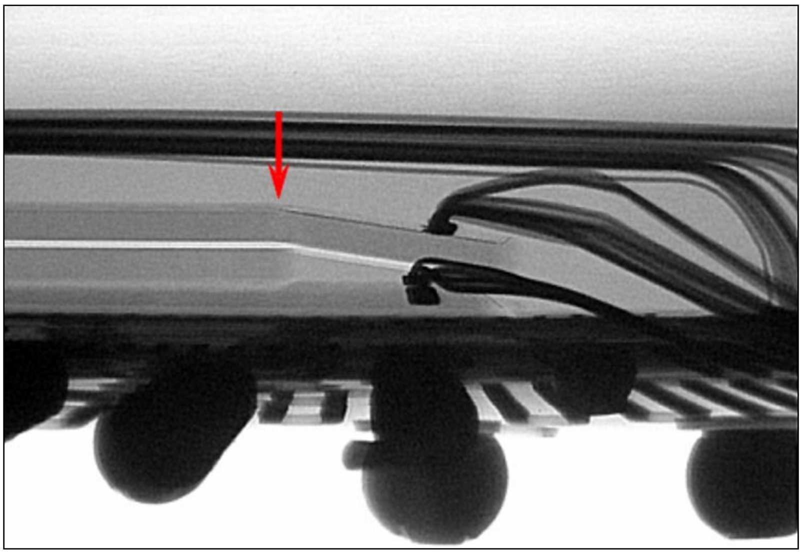


Figure 2 – Crack shown with µCT

space. System-in-package (SiP) fit more functions in smaller spaces by moving some of the complex circuits from the PCB to the package. Moore's law states the number of IC elements on a unit silicon area doubles every 18 months. "More than Moore's" implies Moore's law can be multiplied by the number of stacked silicon chips within a package.

For gaming systems and high-end servers, there is a need for faster and more I/O communication between components. Higher interconnection performance is possible through the shorter interconnects used in stacked components.

Almost every electronic sector has a requirement for stacked components. Even if space or faster I/O communication is not a requirement, by leveraging 3D packaging's infrastructure for high volume, low cost production, system designers can achieve significant savings in PCB real estate and overall cost. As a result, every chip manufacturer includes die stacking in conventional lead-frame-based packages including QFP, MLF and SOP formats.

Electronic inspection

New approaches, such as high density wafer-level bonding or stacking of modules in a cube-like fashion commonly lead to a further exploration of the third dimension in system integration. These technological advances lead to some significant challenges for inspection. Typically to ensure I/O interconnects integrity, (automated) optical inspections are widely used. However, with increasing numbers of hidden interconnects ranging from Flip chip to encapsulated components, inspection techniques need to be deployed which non-destructively visualize internal structures and component compositions in a timely and high resolution manner.

Complexities of stacked packages

Stacked packages have all the normal reliability concerns as single die packages, such as wire bond sweep, flip chip solder reliability and package warpage. Typically these concerns are addressed using 2D X-ray inspection where the 3D space between the tube and the detector is viewed as a 2D image. This is acceptable where there is only one layer of information. In the case of stacked components, the dies are stacked on top of each other, and if a defect is detected, a 2D transmission X-ray cannot separate which of the individual layers contains the defect.

Wire-bond connections

In most 3D packages, the stacked chips are connected along their edges with wire bonds and usually require an extra "interposer" layer between the chips. 3D packages require low-level wire bonding and as the number of wire-bonds increase, the chance of a defect goes up as well. The bond wire must be traced and examined for continuity, non-contact from neighbouring wires, straightness, and maximum deviation from a straight-fitted line. The loop height is checked to verify that it conforms to a given tolerance. 2D X-ray is unable to separate the individual wires and crossing wires are easy to misinterpret.

Thinned die cracking

Stacked packages must be able to maintain the Z-height of a package, requiring dies thinned down to 50µm. Thinned dies make stacked components susceptible to brittle fracture failures when subjected to mechanical shock or during the wire bonding process. Both 2D and 3D X-ray with high contrast detectors can inspect for cracked die.

Thermal concerns

Stacked-die technology presents significant thermal challenges. Greater circuit density means increased power density (W/cm) and more thermal concerns. Die-attach materials must address the excess heat generation. The main risk is that any void in a die attach layer will result in locally increased thermal resistance, consequently causing overheating, and finally might result in damage to the component. Traditional 2D transmission X-ray systems are able to detect voids in die attach, but cannot separate the various layers of die. Therefore the summation of all voids in the stacked package might be calculated as the voiding in a single layer, resulting in a false failure.

Flip chip connections

Flip chip interconnects have better thermal conductive properties than wire-bonds, and the signal speed is faster due to the shorter intercon-

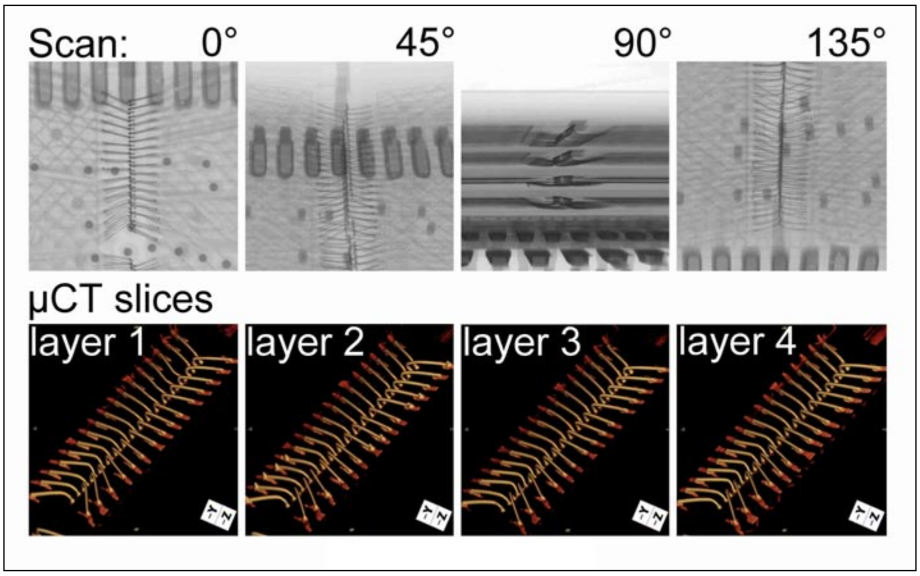


Figure 3 – Scan and µCT slices, provided by NexGen

Computed tomography

Using Computed Tomography (CT), it is possible to virtually cross-section a three-dimensional objects using X-rays. A CT image is typically called a slice, and corresponds to a certain thickness of the object being scanned. Therefore, whereas a typical digital image is composed of pixels, a CT slice image is composed of voxels (volume pixels). These voxels can be combined to form a 3D model for cross-sectioning.

nection distance. Additionally, the rising cost of gold will out-weigh the potential defects of flip chip bumping, include head-on-pillow and solder voiding, increasing the demand for flip chip versus gold wire bonding. These defects are difficult to detect with traditional 2D X-ray systems, yet these defects can be viewed with computer tomography (CT).

Future 3D packages

Most stacked packages greater than 4 devices high use a combination of die and package stacking technologies such as embedded components and System-in-Package (SiP). New technology has been developed to embed electrical components inside the package material. Assembly techniques can place small, discreet passive components inside the package and has now expanded to include active devices, like transistors and integrated circuits.

With SiP, rather than stacking bare die, each die is packaged individually, using chip-scale packaging (CSP) technology, and then stacked afterward. 3D SiPs are similar to die stacks, but instead of tiling dies together, individual subsystems are mounted. As 3D package becomes more sophisticated, Computed Tomography may be required to inspect the complete device.

Inspection of component integrity

High resolution X-ray inspection provides a valuable non-destructive insight of the integrity of a component. 2D inspections assess hidden interconnection points using tools such as automated voiding calculations of die attach, accurate sweep measurement of wire bonds or in depth multiple parameter pass/fail criterion for flip chip solder bumping testing. Through the use of oblique viewing, advanced inspections can be performed on single die components for bonding wire integrity or solder joint open contacts. However, with the technology trends of stacked die and 3D packaging, the need for true 3D X-ray inspections becomes apparent.

3D inspection can isolate areas of interest and ignore information above and below the region of interest. An example is selecting a single die to be easily viewed in a stacked die component. To ease understanding and image interpretation, 3D images can be shown as a cut model, showing where in the sample the analysis is occurring. With precision systems, 3D inspections allow measurements to be performed, regardless of system magnification. Additionally, the dataset can be precisely virtually sliced, such that the same plane of production samples can be repeatedly analyzed automatically.

In conventional radiography, the three-dimensional object situated between the X-ray source and detector is reproduced in the X-ray image on a two-dimensional surface. The 2D image provides limited information, as the position of features can only be differentiated if they are not behind one another in the X-ray image.

A three-dimensional understanding of the sample materializes when radiographic images are captured from different angles. In other words, to obtain a precise representation of the inner and outer geometry of an object to be inspected it is necessary to take X-ray images from as many angles as possible. To generate a 2D dataset, an X-ray beam penetrates the object, and the object's X-ray "shadow" is projected on to a line of pixels where the beam intensity at each pixel is measured. Each such "projection" is obtained at a slightly different angle as the object rotates.

The main limitation for widespread use of µCT is found in typical image acquisition times of 1 to 8 hours. The underlying cause of long scan durations is to improve 2D image quality. The two major image quality requirements that directly correlated to scan duration are:

- Reduction of noise effects
- Limitation of longer-term shifts in geometry or performance

Historically, in order for Microfocus X-ray sources to have small focal spot sizes the X-ray intensity was also low. Low intensity meant that the X-ray image could be significantly affected by back-ground radiation, called X-ray noise. The quality of the final CT image is directly related to the signal-to-noise ratio. Microfocus X-ray systems used image integration for noise averaging where 10 to 100 images would be averaged together, and stray noise would be filtered out. Therefore, the rotation of the sample is paused at predefined steps. At each step the rotation stops for a short period while the X-rays are gathered. These integrations lead to escalating scan times. Additionally, since the intensity was so low, slight shifts in geometry or performance over time (focal spot stability, X-ray intensity, thermal expansion etc.) would have a considerable affect on the repeatability of X-ray output. Other aspects also have an impact on µCT quality and resolution, such as optical distortion in image intensifiers and low sensitivity or acquisition speed of digital panels.

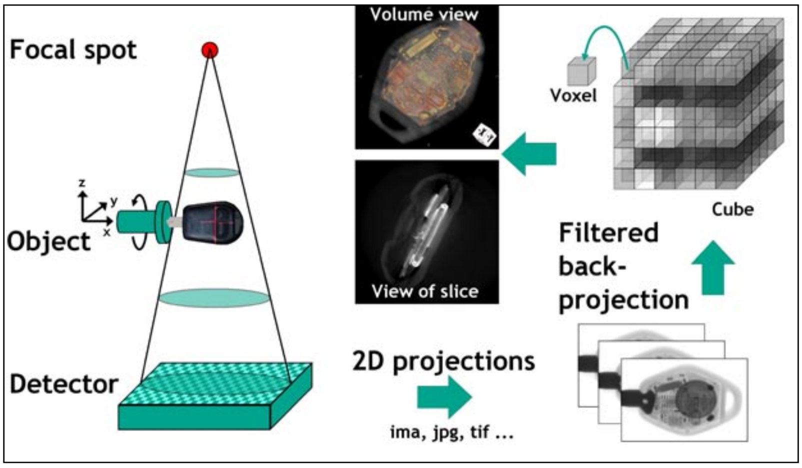
The next step to create the CT image is to back-project the views. “Back-projection” consists of “projecting” each view “back” along a line corresponding to the angle in which the projection data were collected. The back-projections, when enough views are employed, form a faithful reconstruction of the object. On the basis of the back-projections of the X-rays taken at various angles, a cross-sectional image – the so-called tomogram – is calculated via a mathematical algorithm.

Cone-beam CT

Cone beam systems use the full area array of the detector to perform a volume CT. This methodology is based on the cone beam reconstruction algorithm, called the Feldkamp method. An entire volume is generated using one single scan on an array detector. This allows for fast data acquisition, as the data required for multiple slices can be acquired in one rotation. A Feldkamp cone-beam reconstruction is faster than building a volume set from several tomography scans, but there are serious concerns about the X-ray penumbra (the geometric unsharpness caused by the magnified divergence of the X-rays from the centre beam) distorting the final CT volume set. One concern is that as the width of the detector increases, the impact of the penumbra can affect the final resolution of the CT image. Microfocus X-ray technology has a small focal spot to minimize the penumbra effect and has been used for Cone Beam 3D µCT for more than a decade. Another concern is that a pincushion (a geometric, nonlinear magnification across the image) distortion of the 2D image will affect the 3D accuracy.

Subsequently reconstruction software is applied on the cone beam CT volumetric data to produce a stack of 2D slice images of the sample. Until recently, the 2D X-ray scan time greatly exceeded the reconstruction and visualization time, and limited CT to lab environments only.

Figure 4 – Cone beam reconstruction



Technological Advances for Faster µCT

In order to pave the way towards fast µCT inspection the following achievements had to be fulfilled:

- Achieve high X-ray intensity for small focal spot size to reduce noise levels and averaging
- Develop techniques for maximum stability in X-ray intensity and image quality
- Employ advanced detector and reconstruction solutions for implementation of fast µCT.

High-Power Target

As up to 98% of the electrons’ kinetic energy is transformed into heat within the minute focal spot area, thermal stress can lead to target damage. The majority of µCT systems use a directional target X-ray source to achieve high X-ray intensity flux with minimum target damage. Unfortunately, directional target technology cannot achieve the very small focal spots required to resolve advanced interconnect applications. While a transmission target can achieve the small focal spots, typically there is significantly lower intensity. When higher X-ray intensity is desired, as in faster µCT, limitations in heat conductance require broadening the electron beam which defocuses the focus spot and degrades image resolution due to larger focal spot size.

This shortfall has been addressed through the development of a “High-Power” target. A 10-fold increase in thermal conductivity has been achieved compared to conventional transmission targets. Hence high energy electron beams can be kept in focus to maintain small focal spot size for high image resolution. Using a JIMA mask,

Number of projections	*540*	*720*	*1080*
Image acquisition / scanning [s]	18	24	36
Reconstruction time [s]	84	106	162
Sum [s]	102	130	198

Table 1 – QuickScan durations

a test pattern of 2 µm can be clearly resolved even for a target power over 20 Watts.

True X-ray intensity control (TXI)

In Microfocus X-ray tubes electrons emitted at the filament are in essence accelerated towards a transmission target while focussing the electron beam to a small focus spot. While in conventional Microfocus X-ray tubes only the emission current at the filament and the acceleration voltage are controlled, an alternative target technology allows assessment of the true current reaching the target. Based on a continuous feedback, the TXI technology adjusts emission currents in order to ensure maximum X-ray performance stability and hence consistent image quality. This leads to less stringent µCT averaging requirements for the acquisition of a single projection and, even more vital, to more stable projection quality over the 360° sample rotation.

Detectors and reconstruction technology

Image Intensifier detectors require calibration where most digital Flat Panel Area Array detectors are not subject to "pin-cushioning" distortion, and are calibrated or collimated to minimize X-ray penumbra. New developments in flat panel X-ray detector technology have shown that advanced sensor arrays can deliver the high dynamics and resolution required for a fast µCT. A high speed X-ray detector with a pixel size well below 150 µm and a dynamic range better than 2000:1 (contrast resolution is better than 0.5 %) has sufficient contrast resolution to acquire the high intensity X-ray images without integration or averaging, and the pixel size of the detector is smaller than the penumbra geometric unsharpness.

Reconstruction time strongly varies with the number of projections and required µCT resolution. Usually the reconstruction of a cube with 512 x 512 x 512 volume elements (voxels) can take around 15 to 30 minutes with standard reconstruction software. Using a dedicated reconstruction solution with dedicated hardware accelerator boards (the equivalent of 16 coprocessors) achieves a 512^3 voxel reconstruction within 2 minutes.

Ultra-fast µCT

The resulting CT (QuickScan) achieves complete µCT, from initiation of the scanning to inspection of virtual cross-sections in the reconstructed volume model within a couple of minutes.

A comparison for a BGA shows slight variations in the details between a Quality Scan (conventional CT and a Quick Scan (Fast CT). For the conventional µCT illustrated in Figure 5, 1024 projections were acquired and 880 for the QuickScan. Volume views show that both scans enable an in depth inspection of the solder balls and interconnecting surfaces. Minute differences can be seen in surface smoothness. Slices through the BGA show that even small voids can be visualized equally well in the significantly faster QuickScan.

Further examples for high resolution QuickScan applications are depicted in Figure 6. Volume views allow detailed inspections of BGAs and bonding wires. The slice through the illustrated 3 x 3 BGA segment show solder interconnects, micro-vias and voiding. The slice through a single BGA ball even shows the plating and filling of the micro-via below.

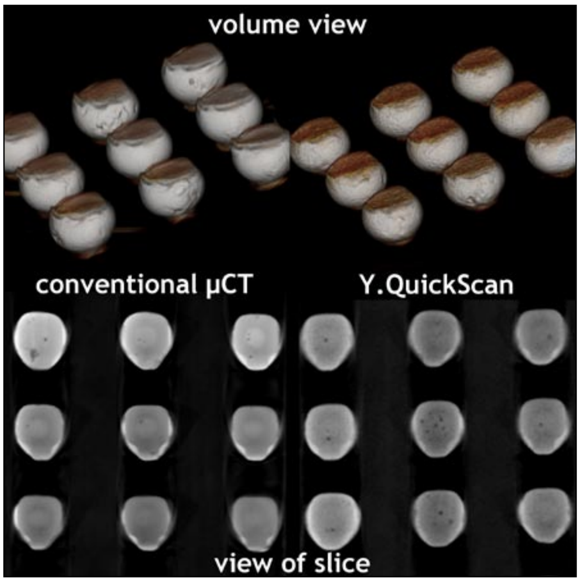


Figure 5 – Conventional µCT (left) and QuickScan (right) of a BGA with volume views (top) and views of a slice (bottom)

Figure 6 – QuickScan - volume view and virtual cross-sections of micro-BGA with micro-vias, wedge bonding