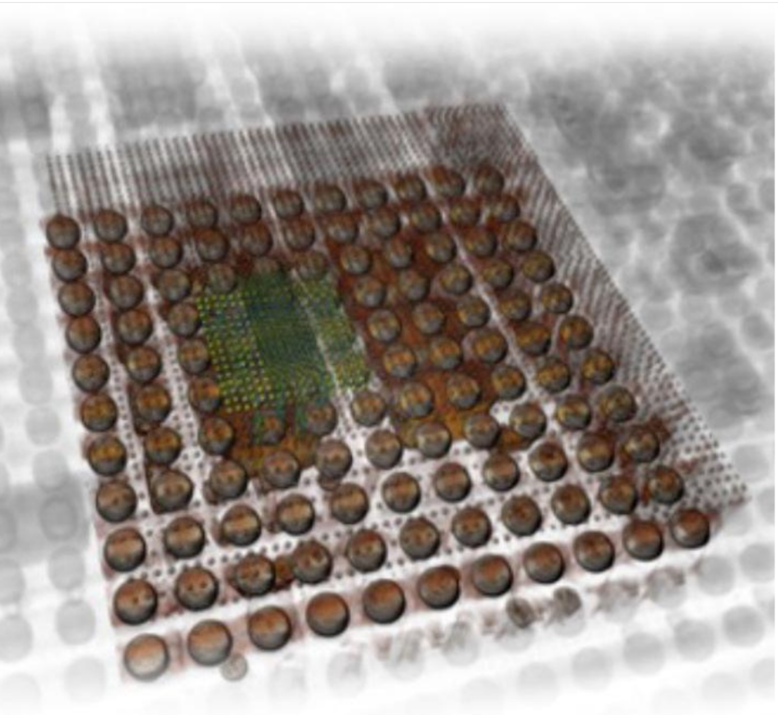
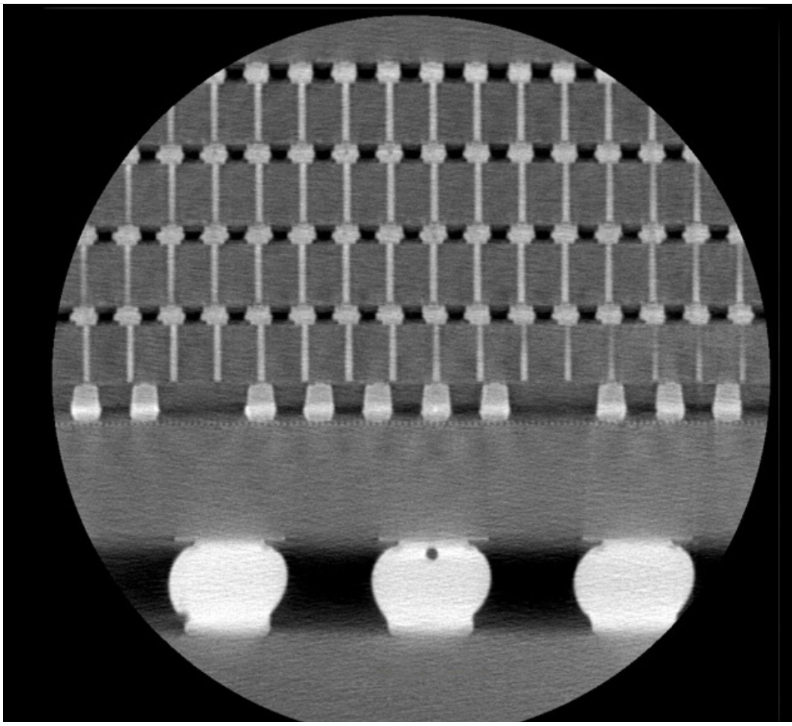
Basics of ZEISS 3D X-ray Microscopy for Semiconductor Package Analysis





Seeing beyond

Introduction

Advances in semiconductor packaging technology are enabling improved system performance. Non-destructive imaging of semiconductor packages has become routine in advanced packaging failure analysis (FA) and process development; ZEISS Xradia Versa family of 3D X-ray microscopes are widely adopted across the industry as the systems of choice for these applications.

This compendium includes five technical briefs about the basics of non-destructive imaging in the FA workflow, why 3D CT is required beyond 2D X-ray, how different X-ray imaging architectures improve resolution, and advances in AI powered reconstruction technologies that improves signal-to-noise, throughput and even recovers resolution in low magnification images. The articles provide a concise summary of the benefits of the ZEISS Xradia Versa in the IC packaging industry to failure analysts, process engineers and semiconductor professionals.

1 Non-destructive X-ray Imaging for Failure Analysis

Before You Do Anything to Disturb Your Sample, Take a Close Look Inside

Advances in semiconductor packaging technology are enabling improved device performance but are also presenting more challenging problems for failure analysts. In this series of Technical Briefs, we explore the critical role of high-resolution 3D X-ray imaging to visualize buried defects within intact devices in a non-destructive manner.

As transistor scaling described by Moore's Law slows, novel packaging approaches have emerged to continue driving device performance. Stacked die in 2.5D and 3D configurations, chiplets and heterogeneous integration approaches, and denser and smaller interconnects have all contributed to the increasing role that packaging technology plays in next-generation semiconductor products.

X-ray Microscopy Streamlines FA Workflow

With the increasing complexity comes greater cost of failures and more challenging failure analysis (FA) tasks. Whether associated with process/package development, quality assurance, or field returns, the FA engineer must provide definitive proof of what (and who) is responsible for the failure.

Non-destructive 3D X-ray microscopy (XRM) has a critical role to play in the ecosystem of FA techniques. Typically following fault isolation, X-ray imaging provides a crucial high-resolution look inside the part prior to any further investigation, including destructive physical analysis. Due to the increasing complexity of modern semiconductor packages, 2D X-ray images are often insufficient for visualizing defects in the failure region, a topic which will be detailed in the third Tech Brief in this series.

Before physically cutting open the sample and risking disturbing the region of interest, use XRM to:

- Determine the likely nature of the defect (crack, void, short, non-wet, etc.)
- Gain a sense of the size of the defect
- Understand how prevalent the defects or features are in the sample
- Better determine where and at what orientation to cut a physical cross section, significantly enhancing efficiency of the subsequent FIB cut if required
- Assess which additional FA techniques might be required

The approach of bypassing X-ray and instead going straight from fault isolation to physical cross sections carries the potential for major risks and time delays.

A single cross-section preparation and imaging workflow can consume a full working day, leading to several-day turnaround times when multiple learning cycles are needed on different samples or different cross-section locations. When the financial impact due to production delays, launch delays, or yield loss can quickly run into millions of dollars, such slow learning cycles are crippling.

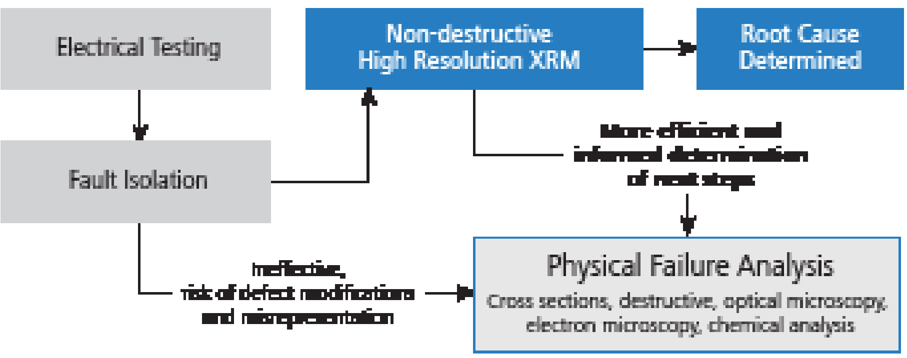


Figure 1 XRM is performed following fault isolation but prior to physical and destructive failure analysis. Visualizing structures in 3D with XRM helps to accelerate downstream processes or can even determine failure root cause.

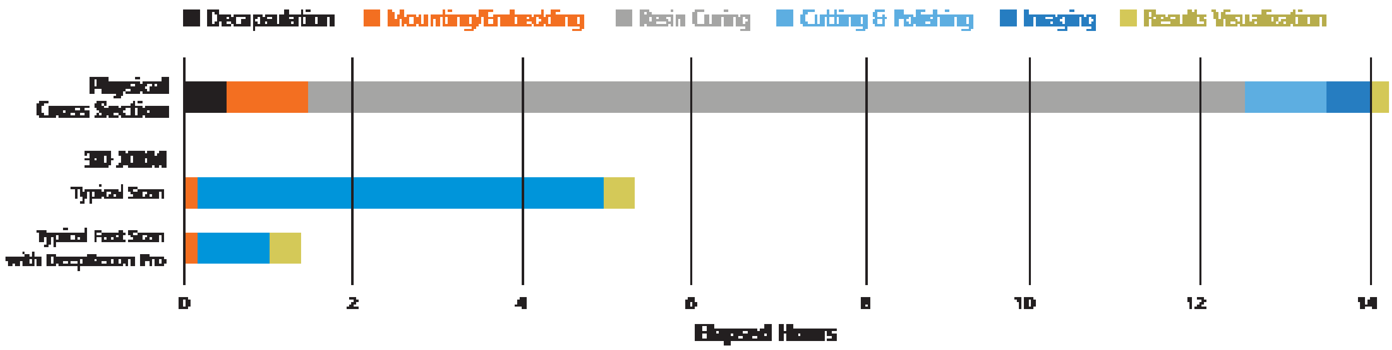


Figure 2 Typical Time-to-Results Comparison of Physical Cross Section with 3D XRM

Reduce Uncertainty in FA

3D X-ray scanning provides data in a matter of hours and produces virtual 2D cross-sections at any location or orientation the user requires. XRM scan times depend on sample characteristics, with two cases shown in Figure 2. (Tech Brief #5 in this series will show how advanced AI-powered tomography reconstruction techniques are now being used to help improve scan throughput by a factor of four.) Furthermore, by using non-destructive 3D visualization to plot a roadmap for the next steps of the FA workflow, you increase total efficiency and reduce the risk of disturbing the region of interest. You also achieve unambiguous, definitive evidence of the contained structures in their native state, avoiding the uncertainty and doubt that can arise the instant a sample is physically modified by a cutting blade or grinding/polishing machine. XRM data provides intuitive 3D results that are easily communicated to colleagues, managers, and other stakeholders.

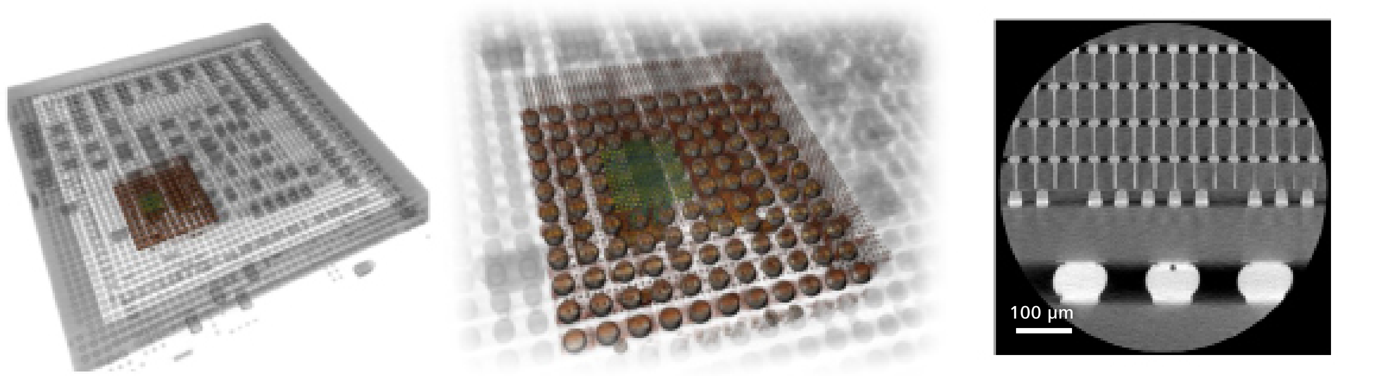
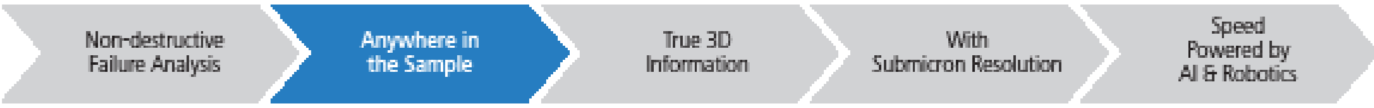


Figure 3 2.5D interposer package imaged by Xradia 620 Versa 3D X-ray microscope at 35 µm/voxel, 11 µm /voxel and 0.72 µm/voxel, respectively.

2 Simple Navigation to the Site of Your Defect

3D Visualization Anywhere in Your Device, at the Click of a Button

Advances in semiconductor packaging technology are enabling improved device performance but are also presenting more challenging problems for failure analysts. In this series of Technical Briefs, we explore the critical role of high-resolution 3D X-ray imaging to visualize buried defects and key structures within intact samples in a non-destructive manner.



Targeting Locations for 3D Scans

As described in Tech Brief 1, X-ray imaging is typically used following fault isolation (for example electrical, thermal, or acoustic testing methods) to visualize and characterize the region of interest prior to destructive techniques.

Because the defect can be anywhere in the sample, the user must be able to easily position the suspected defect in the center of the field of view. For a sample containing multiple defects, the instrument must be able to sequentially position each defect for a tomographic scan by precisely positioning the sample's X/Y/Z coordinates. This is incorporated into the streamlined user workflow depicted in Figure 1.

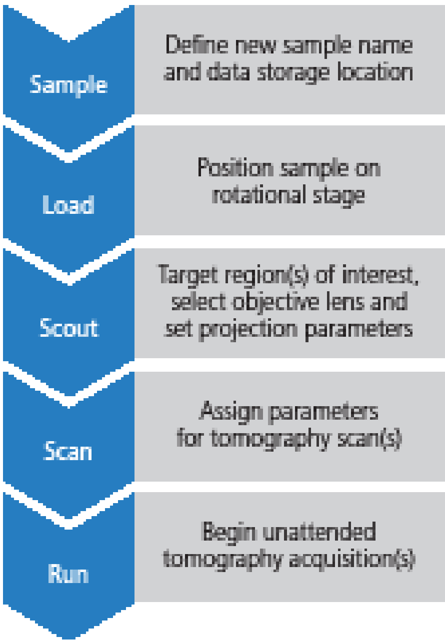


Figure 1 *ZEISS X-ray microscopes are controlled by a mature workflow-based user interface, navigating the operator through several easy steps to prepare their sample for 3D scanning*

ZEISS Xradia microscopes use fully-motorized stages with submicron accuracy to quickly position arbitrary locations for 3D scanning. Live 2D X-ray imaging during set-up enables a user to simply double-click at a position on the device to move it to the center of the field of view, as shown in Figure 2.

Scan Multiple Regions Unattended

For multiple regions of interest, the coordinates and scan parameters specified for each are combined into one scan recipe, which can also incorporate automated vertical or lateral stitching techniques to expand the field of view at a given sample position. These multiple scans are then run back-to-back without human interaction. There is no need to manually remount or re-orient the device between subsequent scans. This entire procedure is enabled through a workflow-based user interface, which guides the operator through sample setup, as shown in Figure 1.

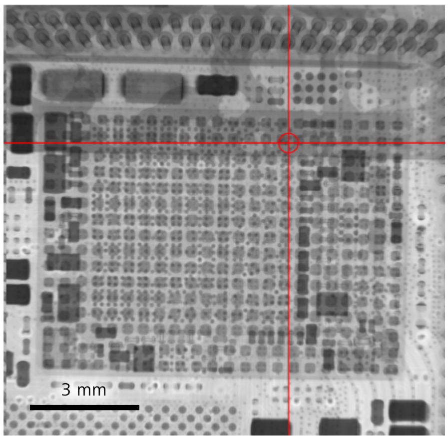


Figure 2 *During the 'Scout' step of preparing an X-ray scan, the operator uses a live 2D view to position any location of the device for high resolution scanning. A double-click directly on the live image, as depicted by the red crosshairs, repositions the sample to place the desired location at the center of the tomography rotation axis and field of view.*

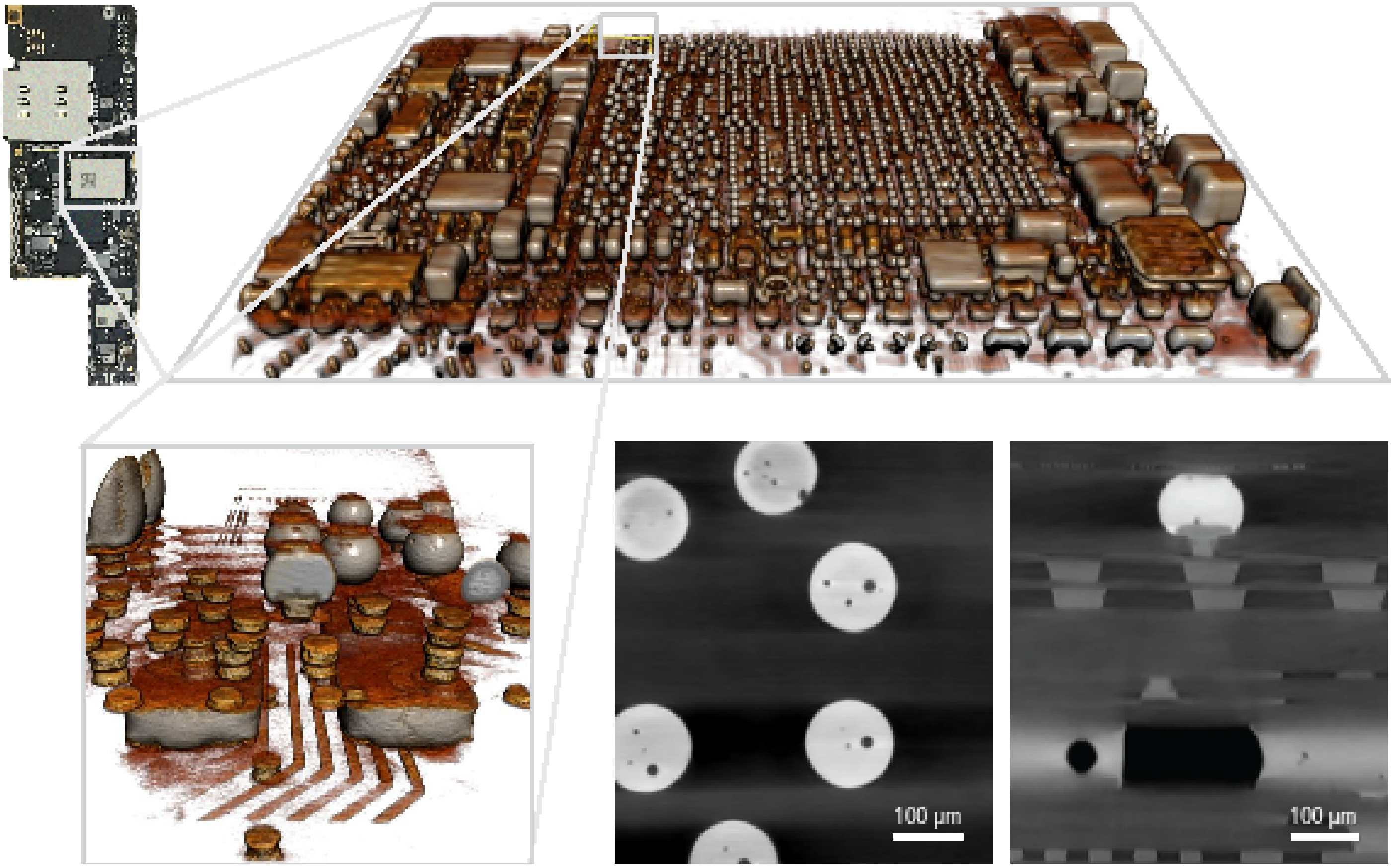


Figure 3 *3D XRM scan of the sample depicted in 2D in Figure 2. An initial scan at moderate resolution captured nearly the entire wifi/Bluetooth module. The sample was then repositioned to target a specific location with a high resolution scan. Multiple such targeted scans can be run in succession without user intervention or re-mounting the sample. First appeared in Harris et al., IRPS 2022*

An operator returning to the instrument at the conclusion of all scans will immediately receive 3D visualizations and 2D virtual cross sections of each region of interest, if auto-reconstruction is implemented. The scan data is spatially registered in 3D space along with the associated position coordinates. The example in Figure 3 depicts the analysis of the zwifi/bluetooth module from a smartphone. The photo shows the module still mounted on the board which was loaded into the X-ray microscope. An initial scan captured nearly the entire module, while a subsequent high-resolution scan targeted a specific off-center region (positioned as shown in Figure 2). Virtual cross sections show the results of the high resolution scan.

3 Data Fidelity through 3D Imaging

Fully Understanding 3D Defects within 3D Structures Requires 3D Visualization

New semiconductor packaging technologies are utilizing 2.5D and 3D designs with stacked die to improve performance and increase the functionality delivered from a given device footprint. These architectures can utilize multiple layers of dense, fine-pitch interconnects.

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X-ray Imaging Techniques

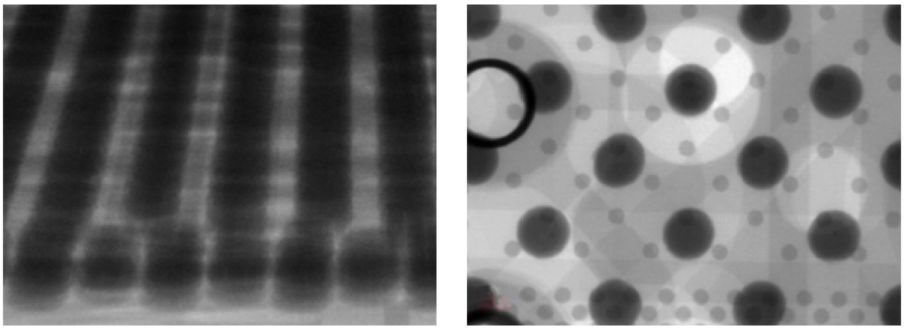
X-ray imaging inspection can be approached using three different types of data acquisition:

- *2D X-ray* – using radiographs, or projections, through the sample
- *2.5D X-ray* – partial angular rotation of the sample generates distorted images with incomplete volumetric information
- *3D X-ray* – tomography using a full angular rotation of the sample; produces true volumetric datasets with isotropic data elements (voxels)

Tech Brief 1 illustrated examples of how non-destructive X-ray imaging can help mitigate major business risks, inefficiencies, and ambiguities compared to an FA workflow that goes directly from fault isolation to physical cross sectioning. However, not all X-ray imaging approaches are created equal in this regard and, of the three techniques listed above, only true 3D X-ray tomography provides a comprehensive and definitive picture of the structures within advanced packages.

2D X-ray Imaging

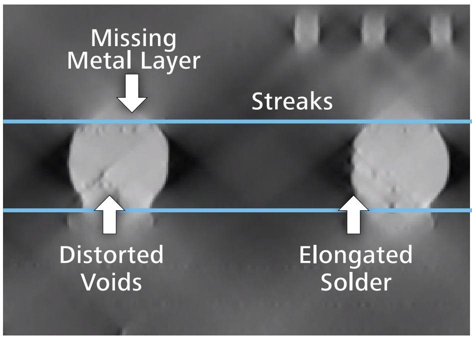
- Useful for very large/gross defects or features in packages built from mature technology
- For advanced package designs, 2D X-ray projections can miss key details due to the nature of "overlapping" features and layers in the image
- Sample tilting is often insufficient to remove the spatial ambiguity
- Small internal defects are often difficult or impossible to see due to insufficient contrast, resolution, and 2D geometric distortion



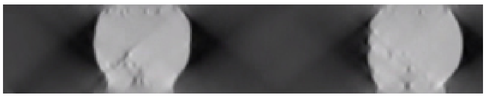
2D X-ray imaging often fails to reveal embedded defects due to the lack of 3D geometric information.

2.5D X-ray Imaging

- Uses either partial angular rotation or laminography approach
- Both approaches provide inadequate sampling of the Fourier space to enable a proper volumetric reconstruction
- While sometimes described/marketed as 3D since very thin slices of a data volume are produced, these 2.5D volumes are "pancake-like" in geometry, contain no useful information in the Z direction, and suffer from prominent "missing wedge" streak and blur artifacts
- 2.5D X-ray imaging based on limited angular rotation or laminography suffers from missing data and strong angular sampling-related artifacts. These artifacts are hidden when data is cropped to the middle of the volume, also eliminating important information of the key interconnects.



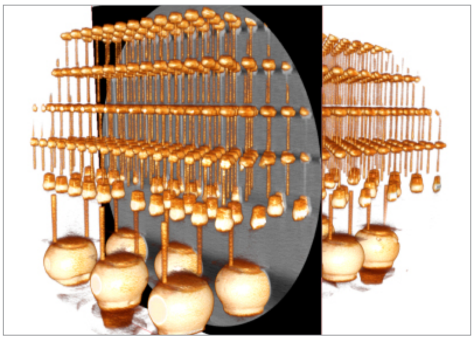
Laminography – cropped slice hides artifacts

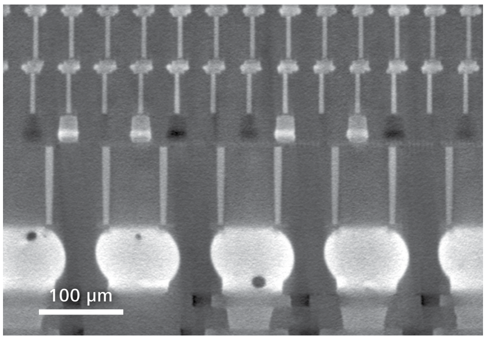


Arrows in the left image point out distortions and missing information from the limited angle 2.5D approach. The cropped image shows that the artifacts at the top and bottom of the slice are hidden. The blue lines are the cropping boards.

3D X-ray Microscopy Imaging

- True 3D data acquisition with full angular rotation of the sample for a complete tomographic reconstruction
- Visualization as 3D renderings or unlimited possibilities of virtual 2D cross sections at different orientations and locations
- Observe the true structure of defects (i.e. cracks oriented in-plane or out of plane) that cannot be visualized by 2D or 2.5D X-ray imaging techniques





3D X-ray tomography provides true 3D information with isotropic resolutions at all three XYZ axes and is viewable by 3D renderings or virtual 2D cross sections

In failure analysis, data fidelity is crucial to pinpointing the process and/or party responsible for generating the defect. 3D X-ray scanning provides the most comprehensive, unambiguous, and intuitive depiction of what is happening inside the 3D volume, with results that can be easily and confidently communicated to relevant stakeholders to determine corrective actions and resolve the problem quickly.

4 Resolution-at-a-Distance
Achieving 3D Visualization of Submicron-Scale Features Inside Large Semiconductor Packages

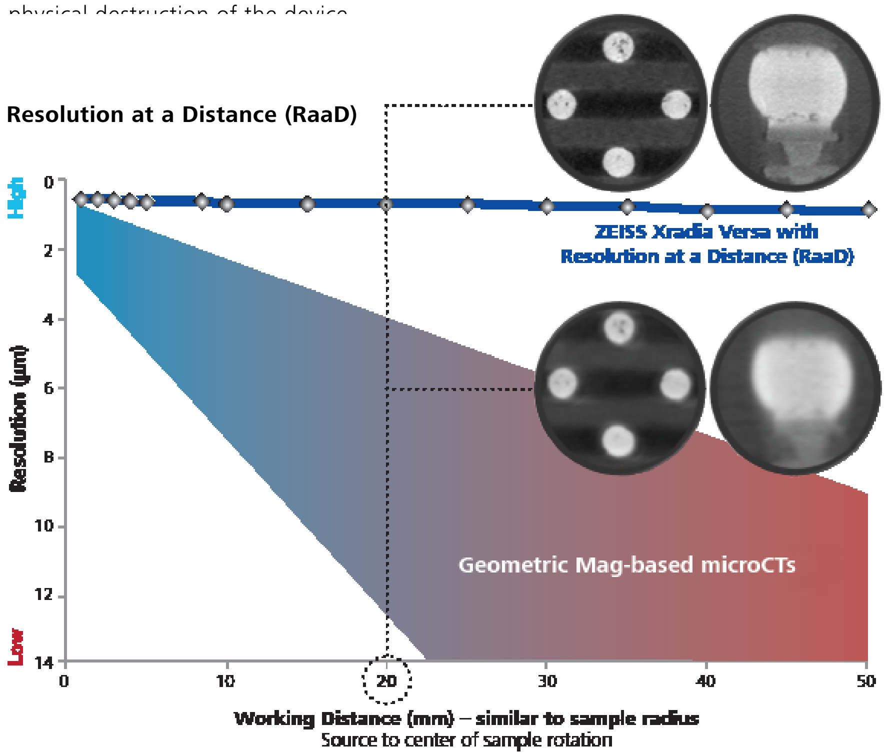
Advances in semiconductor packaging technology are enabling improved device performance but are also presenting more challenging problems for failure analysts. In this series of Technical Briefs, we explore the critical role of high-resolution 3D X-ray imaging to visualize buried defects and key structures within intact samples in a non-destructive manner.

While semiconductor packages range from a few millimeters to multiple centimeters in size, industry trends towards heterogenous integration of multiple chiplets within a given package are driving an evolution towards increasing interconnect complexity and density. But for failure analysis engineers, the goal often remains the same: obtain as much information as possible about the failure in a non-destructive manner prior to physical destruction of the device.

The Sample Size Problem

In X-ray imaging instruments, the sample size ends up manifesting itself in the concept of "working distance", defined as the distance between X-ray source and sample. For 3D X-ray scanning, this distance must be large enough to permit rotation of the sample, so in most cases the working distance can be approximated as half the package width (i.e. sample radius). Therefore, larger packages tend to require larger working distances.

Working distance is an important concept because different types of 3D X-ray tools handle it very differently. Most commercially available CT or microCT systems use an instrument design where performance is highly sensitive to working distance. These instruments, which use "geometric magnification" to project X-ray images onto a flat panel detector, suffer from a steep linear degradation of image resolution as sample sizes become larger than a few mm. For today's semiconductor packages, this can be a major problem, as small defects will no longer be visible in the resulting 3D data.



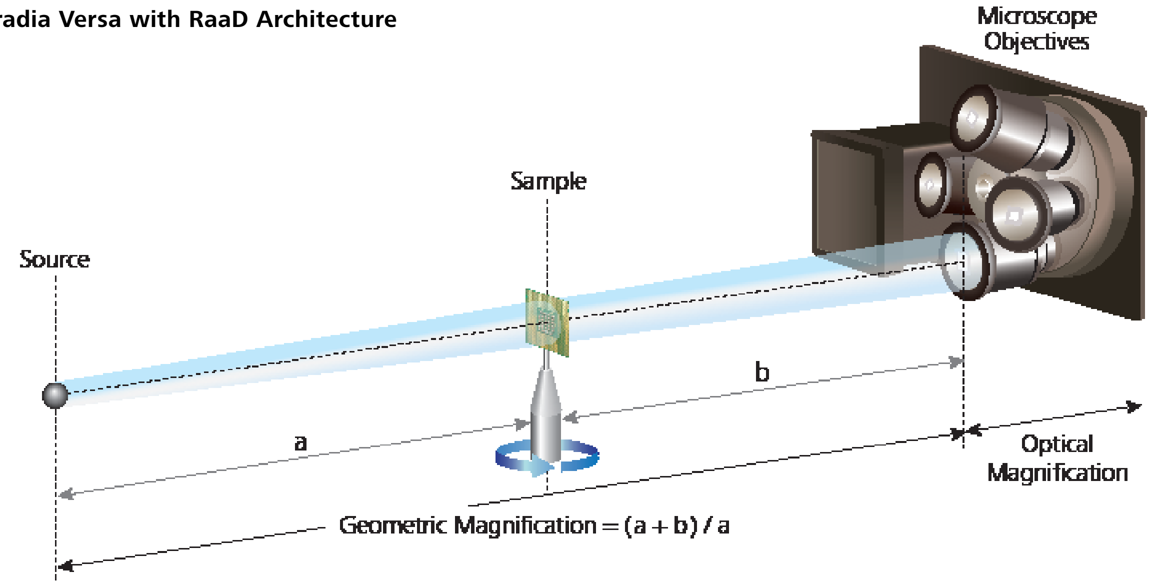
Resolution at a Distance solves the sample size problem.

The ZEISS XRM Solution: RaaD

ZEISS microscopes address this problem with a technology called Resolution at a Distance (RaaD), which is implemented on ZEISS Xradia Versa X-ray microscopes. In the Versa design, a selection of interchangeable scintillator-coupled optics is incorporated within the detector assembly to further magnify the X-ray image.

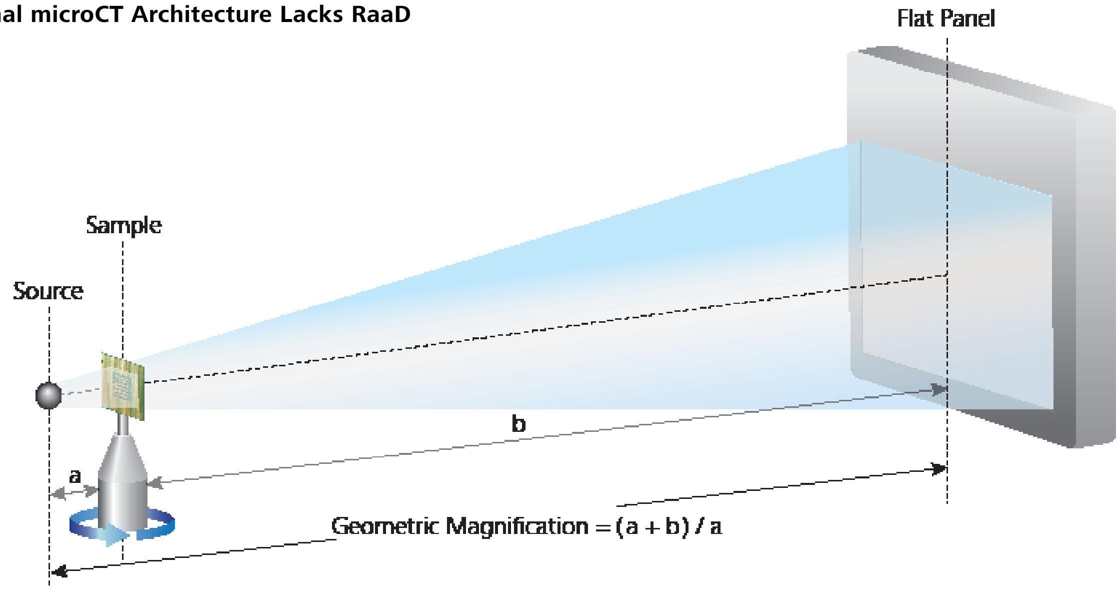
With the combination of geometric magnification, this optics design substantially minimizes substantially minimizes the dependency of resolution on working distance, meaning that even medium and large-sized packages can be examined at high resolution by using the optical magnification system to zoom in on regions of interest in 3D at various locations within the device.

ZEISS Xradia Versa with RaaD Architecture



Unique XRM architecture with scintillator-coupled optics minimizes dependency of resolution on sample size.

Traditional microCT Architecture Lacks RaaD



Traditional microCT architectures rely on high levels of geometric magnification and therefore very small sample sizes to achieve high resolution.

5 Efficiency in the FA Lab
3D X-ray Workflow Speed Powered by AI & Robotics

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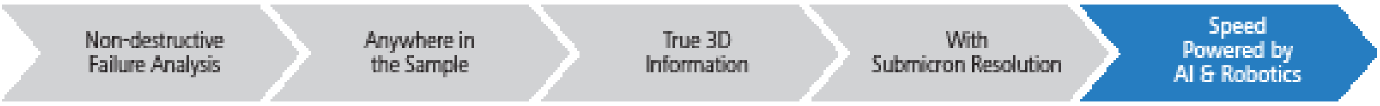
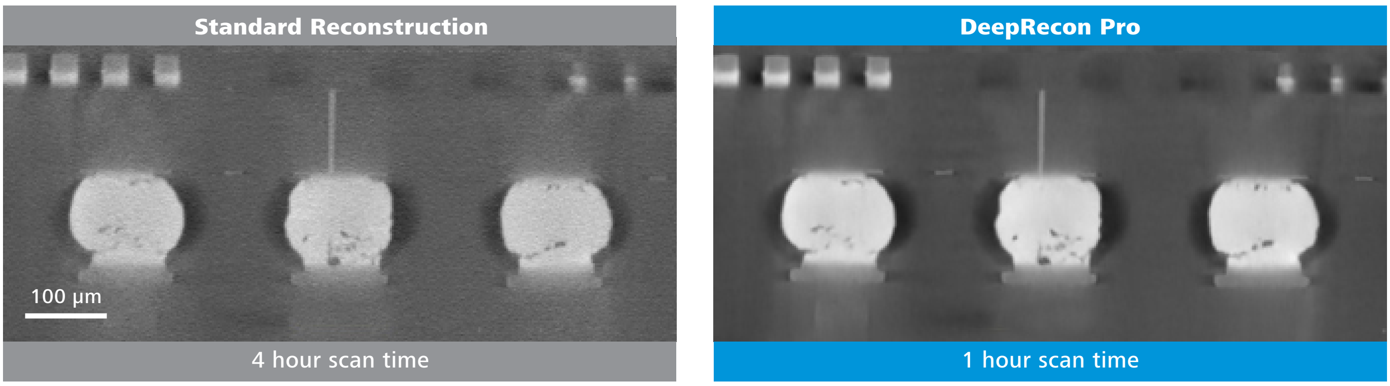


Tech Brief 1 in this series discussed how X-ray microscopy (XRM) plays a critical role in package FA prior to physical cross sectioning by increasing efficiency and success rates while reducing the risk of inadvertent sample damage. To fully realize these benefit, XRM must be able to scan intact packages with both high spatial resolution and high throughput.

Intended to enhance the efficiency of FA labs, ZEISS DeepRecon Pro, an AI-powered reconstruction method, enables faster 3D X-ray scans while preserving ZEISS's revolutionary Resolution at a Distance (RaaD) and image quality advantages.

Up to 4X Faster Scans
DeepRecon Pro enables faster high-resolution, high-quality 3D X-ray image acquisition workflows used in FA and packaging development. Up to 4X faster throughput is possible by leveraging ZEISS's deep learning network models specifically tuned for high-resolution 3D X-ray microscopy.

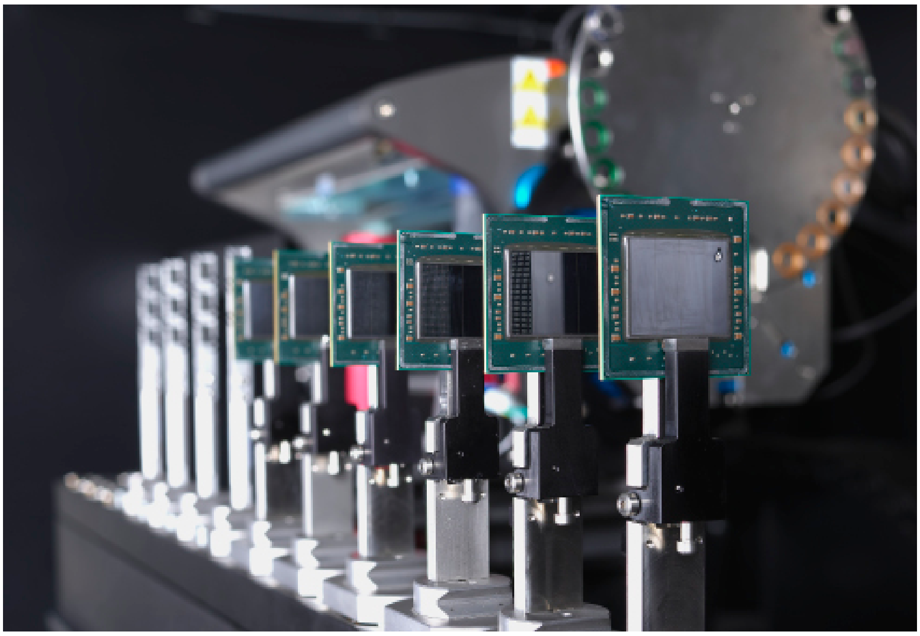
Better Image Quality
DeepRecon Pro offers a statistically improved contrast-to-noise (CNR) ratio, producing the highest quality images for improved visualization of defects and small and low-contrast features.



DeepRecon Pro reconstruction improves throughput by 4X for a sample containing C4 bump cracks. First appeared in Gu et al., "Accelerate your 3D X-ray failure analysis by deep learning high resolution reconstruction," in Proc. 47th Int'l Symp for Testing and Failure Analysis, 2021.

Improve XRM Productivity with Robotics

- Recipe-based acquisition set ups enable multiple scans to run sequentially at different sample locations under different scan settings without user intervention.
- An optional Autoloader robot handles 14 sample holders (containing 14 or more samples, depending on mounting technique), scripted to run sequential for as long as several days without user intervention.



An Autoloader robot can be incorporated to allow unattended operation of the instrument by scanning many samples for multiple days at a time.

While conventional wisdom suggests "3D X-ray scanning is too slow", the improvements in technology described in this Tech Brief make that statement much less true today than it was in the recent past. Typical scans no longer require overnight runs. Instead, numerous datasets on multiple samples can easily be acquired within a day or single shift. This dramatically improves time to result, allowing the failure analysis engineer to quickly determine next steps while reducing the backlog for scanning additional samples on the instrument.

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