Non-destructive, High-resolution Fault Imaging for Package Failure Analysis
with 3D X-ray Microscopy
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As the semiconductor industry approaches the limits of CMOS scaling, traditional planar methods can no longer keep pace with Moore’s Law. To continue producing ever-smaller, ever-faster devices with low power requirements, the industry has turned to package innovation through 3D stacking of chips and novel packaging formats, a trend labeled “More than Moore.”

Advances in electronics packaging are fueled by consumer demand for greater bandwidth in mobile devices. The technological answer is to utilize 3D system integration, increase the interconnect count and shrink the pitch, solder volume and height. This results in packaging architectures that are growing increasingly complex, producing new manufacturing challenges and increased failure risks. Furthermore, since the physical location of failures are often buried within these complex 3D structures, conventional methods for visualizing failure locations are becoming less effective. New techniques are required to isolate and determine the root cause of failures. ZEISS Xradia 3D X-ray microscopes (XRM) provide an effective solution to the critical need for non-destructive submicron and nanoscale imaging of defects buried within intact 3D packages.

Developments driving new requirements for characterization in the semiconductor industry include the following.

Complex Packaging with Finer Bumps and Smaller Features
Wire bonds and solder bumps continue to decrease in size. As features shrink, formerly benign small defects begin to significantly impact reliability. At the same time, requirements to use lead-free solder have increased delamination and crack risk.

Higher Number of Interfaces
Interfaces in 3D packages, either in the interposer and fan-out layers or in multiple die stacks, have grown in number, which obscures the visibility of defects below the surface for conventional non-destructive techniques.

Through Silicon Vias (TSVs)
TSVs vertically connect chips or devices and are considered one of the key enabling technologies for 3D architectures. TSV fabrication is not yet mature and significant defects can occur, especially in smaller TSVs (1-5 μm). These failures include voids during metallization, die cracking induced by the large thermal expansion mismatch between silicon and the conducting via material, or reliability failures during stress testing.

Figure 1 Versa reconstructed 3D dataset and virtual cross section of a 2.5D device
ZEISS Xradia Versa and Xradia Ultra families of 3D X-ray microscopes provide the highest resolution and contrast capabilities for computed tomography, beyond traditional micro-CT. These instruments solve emerging imaging challenges for next-generation semiconductor packaging.

**ZEISS Xradia Versa for package level failures**

ZEISS Xradia Versa provides failure analysts with non-destructive imaging capabilities at submicron resolution for large intact packages without destructive sample preparation, which could otherwise alter defects. This solution has proven to be a valuable precursor and even a replacement for physical failure analysis (PFA) for package level failures such as cracks in bumps or microbumps, solder wetting problems or TSV voids in the micrometer or above size range. Visualizing failures non-destructively before PFA enables failure analysts to increase FA success rates by determining the best cross-section orientation before PFA.

![Diagram of the two stages of Versa optics: geometric and optical magnification](image1)

![Virtual cross section examples of package-level defects that are commonly imaged with Versa](image2)

**Figure 2** Virtual cross section examples of package-level defects that are commonly imaged with Versa

**Figure 3** Diagram of the two stages of Versa optics: geometric and optical magnification

Geometric Magnification = \((a + b) / a\)
ZEISS Xradia Ultra for CPI and BEOL failures

ZEISS Xradia Ultra offers the highest resolution of all laboratory 3D X-ray inspection tools, reaching 16 nm pixel (50 nm spatial) resolution that uniquely enables non-destructive imaging of µbumps, chip-package-interactions and back-end-of-line (BEOL) die level failures. The innovative Xradia Ultra architecture employs proprietary X-ray optics originally developed for synchrotron facilities and optimized by ZEISS for a wide variety of lab-based applications. The Ultra has two imaging modes delivering 150 nm and 50 nm spatial resolution respectively.

Figure 4 (Top left) 3D reconstruction of BEOL features from an advanced device; (Top right) Virtual cross section showing BEOL and bump interface; (Bottom row) Virtual cross sections isolating individual BEOL metallization layers.

Figure 5 Diagram of Ultra optics showing the X-ray capillary condenser, Fresnel zone plate objective, Zernike phase ring (optional) and the detector.
Step-by-Step: A New Failure Analysis Workflow

The combination of submicron and nanoscale XRM provides a unique workflow for failure analysis that can significantly enhance the success rate.

The high resolution and large working distance of Versa provides a detailed picture of package-level failures before committing to destructive physical failure analysis (PFA). In many cases this may be enough information to determine root cause. At the very least, the valuable insights from the 3D dataset will help optimize subsequent PFA.

For diagnosing die-level or CPI-related failures, ZEISS Xradia Ultra’s nanoscale resolution offers unique capability to image failures in 3D without disrupting the defect area. Like Versa, imaging failure locations with Ultra provides insights that may improve the success rate of subsequent high-resolution PFA (e.g. TEM imaging).

Initial Fault Isolation

Non-destructive techniques (NDT) such as electrical TDR, electro optical terahertz pulse reflectometry (EOTPR), or thermal, acoustic, or magnetometry microscopy is used to identify the approximate location of the fault within the package.

Xradia Versa Submicron Fault Imaging

Using the output of the previous step, ZEISS Xradia Versa can virtually zoom in on the region of interest within an intact package to produce submicron 3D images.

Virtual cross sections and delayering of the 3D datasets may be accomplished from any desired angle of interest providing fine defect localization and visualization for classification. Defects and other buried areas of interest inside the sample can be exposed and highlighted without invasive procedures that might alter or destroy the original root cause evidence. For package-level failures, the next step is PFA. Knowledge of the fault’s physical characteristics and orientation helps maximize FA success by informing the optimum approach for PFA.

Figure 6 Package FA workflow including submicron and nanoscale XRM

Figure 7 (Top left) Short detected at BC14; (Top right) Orientation of short is not clear from electrical test or 2D X-ray; (Bottom) Versa 3D image clearly shows orientation of the short, which provides valuable guidance for PFA

Source: Chip Scale Review, September/October 2018.
Advanced Fault Isolation (e.g. EBAC, PEM, OBRICH, etc.)
As FA continues, advanced fault isolation techniques pinpoint the potential defect area towards die-level features such as CPI or BEOL.

Sample Preparation for Ultra
With the fail site identified to a localized physical area, sample preparation is focused on preserving the defect site while reducing the sample volume for further imaging. A picosecond laser is used to prepare the sample for imaging by Ultra in a workflow that achieves a suitable sample in under an hour with high success rates. For optimum results, a 70 µm maximum sample diameter is recommended.

Xradia Ultra Nanoscale Fault Imaging
Xradia Ultra allows feature imaging with spatial resolution in the range of 50–150 nm. This approach yields 3D reconstruction at sufficient resolution to expose the internal device layout non-destructively. As a next step, virtual delayering and cross-sectioning techniques are used to image the failure location or to reveal individual layers such as top- or bottom-wafer interface and interconnects.

PFA and root cause determination (destructive)
Downstream, last-step electron microscopy techniques, such as mechanical cross-sectioning or focused ion beam tomography (FIB-SEM), use high-resolution fault isolation information provided by Xradia Versa and Ultra to navigate to the defects and characterize them at subnanometer resolution.

Figure 8 Desired region cut out using ps-laser ablation

Figure 9 (Left) Region of interest (ROI) is highlighted. (Right) Ultra 3D image of ROI at 150 nm spatial resolution

Figure 10 Virtual cross sections of 3D datasets created by Ultra using 150 nm and 50 nm resolution modes respectively