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Advancing Semiconductor Packaging with Micro- and Nano-Scale 3D X-Ray

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ABSTRACT

As semiconductor packaging scales toward fine-pitch architectures like hybrid bonding, nondestructive testing (NDT) is increasingly important for detecting and classifying critical defects. Using state-of-the-art 3D X-ray microscopes, automated, closed-loop routines can identify, measure, and classify defects such as fine-pitch alignment errors and microscopic voids during autonomous part inspection. This modernization of NDT is enabled by combining hardware and digitalization advancements, including evolutionary improvements in hardware platforms and data-driven approaches to analytics. Advances in micro-CT and nano-CT provide the volumetric resolution essential for quantifying material integrity and interconnect geometry within complex assemblies. When paired with automated data analysis routines, these approaches deliver reproducible metrics, including stand-off height, void content, feature sizes, and shape classification. The combination of non-destructive, high-resolution imaging and automated data analysis drives robust process development, accelerating the maturation of next-generation packaging processes to meet the evolving requirements of the semiconductor industry.

Keywords: X-Ray Computed Tomography, X-Ray Computed Laminography, Semiconductor, 3D Inspection

INTRODUCTION

The continued scaling of semiconductor packaging toward fine-pitch and three-dimensional integration architectures, such as hybrid bonding, chiplet integration, and advanced wafer-level packaging, has significantly increased the complexity of interconnect structures and tightened tolerance requirements for critical features. As interconnect pitches shrink and bonding interfaces become buried within multilayer assemblies, the ability to detect, classify, and quantify defects without destroying the device is essential for both process development and manufacturing control.

Conventional inspection and metrology techniques face inherent limitations in this context. Optical microscopy lacks sufficient penetration depth and volumetric access to evaluate buried interfaces, while destructive methods such as cross-sectioning are time-intensive, introduce variability, and are incompatible with inline or iterative feedback during process optimization. These challenges motivate the adoption of nondestructive testing (NDT) approaches capable of providing high-resolution, three-dimensional insight into advanced packaging structures.

X-ray–based imaging, particularly three-dimensional X-ray microscopy, has emerged as a powerful NDT solution for advanced semiconductor packaging. Recent advancements in micro-computed tomography (micro-CT) and nano-computed tomography (nano-CT) have significantly improved volumetric resolution, contrast, and system stability, enabling visualization of features at length scales relevant to fine-pitch interconnects. When combined with automated and data-driven analysis techniques, these imaging capabilities support a shift from qualitative inspection to quantitative, reproducible characterization of packaging integrity.

EXPERIMENTAL SYSTEM

The experimental system used in this work is a laboratory-based 3D X-ray microscope designed for nondestructive evaluation of devices in their natural states, including advanced semiconductor packages, printed circuit boards (PCBs), and intact wafers (up to 300 mm). Instead of relying on lenses or zone plates, the system achieves high spatial resolution through geometric magnification, enabling imaging of fine-pitch interconnects and bonding interfaces while preserving high X-ray flux and contrast.

The system supports both computed tomography (CT) and computed laminography (CL) acquisition modes. CT is used for fully rotatable samples to provide isotropic volumetric reconstructions, while CL enables three-dimensional imaging of large-area, planar samples (such as packaged devices or bonded wafers) where full rotation is impractical. The availability of both modes within the same platform allows inspection workflows to be adapted to a wide range of sample geometries encountered during advanced packaging development.

A key capability of the system is its ability to zoom into localized regions of interest, achieving spatial resolution down to approximately 0.35 μm. This zoom capability enables hierarchical inspection workflows, in which larger fields of view are used to survey assemblies for potential defects, followed by higher-resolution CT or CL scans to quantify critical features such as hybrid bonding interfaces, fine-pitch misalignment, and microscopic voids.

Automated alignment and recipe-based acquisition workflows support repeatable data collection across samples and inspection conditions. Volumetric reconstruction outputs are directly compatible with automated analysis pipelines for defect detection and quantitative metrology. The combination of lensless high-resolution imaging, dual CT/CL acquisition modes, and digital workflow integration makes this experimental system well suited for nondestructive, quantitative characterization of next-generation semiconductor packaging architectures.

TEST METHODOLOGY, RESULTS AND DISCUSSION

Computed tomography (CT) and computed laminography (CL) provide complementary nondestructive imaging capabilities for advanced semiconductor packaging. CT offers the most precise and nearly isotropic cross-sectional reconstructions, making it well suited for detailed analysis of localized features such as interconnect geometry, void morphology, and delamination at bonded interfaces. Its full-rotation acquisition geometry enables excellent depth fidelity and quantitative measurements at the highest achievable spatial resolution. However, CT is constrained by sample size and geometry, which limits its applicability for large, planar structures. In contrast, CL relaxes these geometric constraints through a limited-angle acquisition, enabling scalable three-dimensional imaging of intact printed circuit boards and full 300 mm wafers with minimal sample preparation. CL also supports faster scan times and reduced X-ray dose, making it well suited for large-area inspection and process screening. These advantages come with trade-offs in cross-sectional image quality and directional resolution compared to CT, reflecting a balance between scalability and ultimate image fidelity.

By leveraging this dual-mode approach, the nondestructive testing (NDT) engineer can select the most appropriate imaging geometry for each device under test (DUT), optimizing inspection performance for the specific application. This flexibility enables both high-resolution, nanoscale X-ray tomography for detailed defect analysis and scalable computed laminography for large-area inspection within a single inspection platform, while minimizing laboratory footprint and infrastructure requirements.

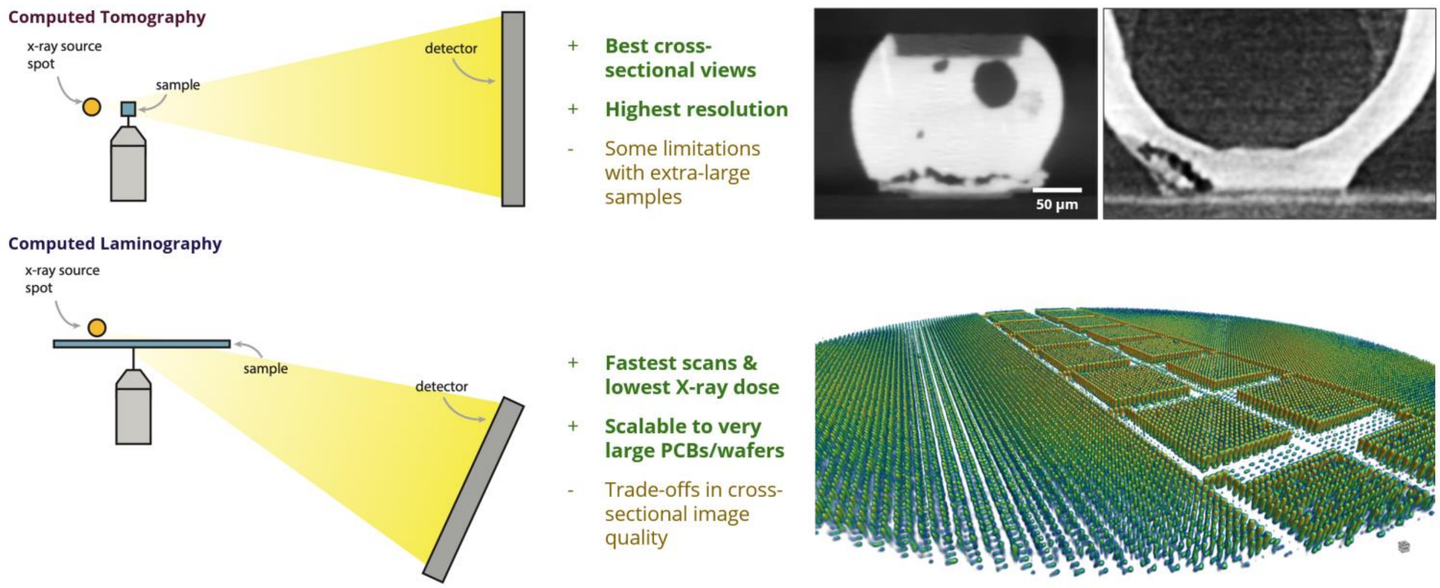

Figure 1: Comparison of computed tomography (CT) to computed laminography (CL) 3D X-ray imaging architectures. The CT approach (top) provides the highest-quality cross-sectional views, while the CL geometry (bottom) provides scalability of high-resolution 3D X-ray to large PCBs and 300 mm wafers.