

Development of a High-resolution X-ray 3D Imaging System for Inspection of High Bandwidth Memory

Jaeyoung Im^a, Sung Oh Cho^{a*}

^aDepartment of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

*Corresponding author: socho@kaist.ac.kr

***Keywords** : High-resolution, X-ray imaging, 3-dimension, High bandwidth memory

1. Introduction

With the rapid advancement of high-performance computing (HPC), artificial intelligence (AI), and data-center technologies, the demand for high-bandwidth memory (HBM) has significantly increased. HBM devices consist of vertically stacked DRAM dies interconnected through Through-Silicon Vias (TSVs) and micro-bumps. Due to this complex 3D architecture, internal defects such as TSV voids, micro-bump misalignment, cracks, and delamination can critically degrade performance and yield.

Therefore, non-destructive 3D inspection during manufacturing is essential to ensure reliability and productivity. X-ray inspection is widely adopted for internal defect detection in advanced semiconductor packaging. However, conventional high-resolution 3D X-ray imaging systems rely on geometric magnification using micro-focus X-ray tubes with very small focal spots. While these systems achieve high spatial resolution, their limited output power severely restricts inspection throughput. As a result, acquiring high-resolution 3D datasets can require tens of minutes per device, which is incompatible with inline semiconductor manufacturing environments.

To address this limitation, this study proposes an optically coupled high-resolution X-ray 3D inspection system for HBM devices. By decoupling the X-ray focal spot size from the spatial resolution using an optical magnification approach, the system enables high-speed 3D imaging while maintaining sufficient resolution for TSV and micro-bump inspection.

2. Methods and Results

2.1 Design of Fast X-ray 3D Imaging System for HBM Inspection

2.1.1 Object – HBM Stacked Memory Package

The inspection target is an HBM stacked memory package consisting of multiple DRAM dies vertically interconnected through TSVs. The structure includes:

- TSV arrays within silicon dies
- Micro-bump interconnections between dies
- Underfill materials

- Redistribution layers (RDL)
- Substrate interconnects

The critical defect sizes to be detected are typically in the range of 5–20 μm (TSV voids, micro-cracks, bump defects), requiring high spatial resolution and high contrast sensitivity.

To determine optimal X-ray energy conditions, preliminary simulations and reference experiments were conducted considering silicon, copper TSVs, and underfill materials. The optimal tube voltage was found to be in the range of 80–120 kVp, providing sufficient penetration through stacked silicon while maintaining contrast for TSV and bump defects.

2.1.2 Decoupling X-ray focal spot size from spatial resolution

In conventional geometric magnification-based X-ray systems, spatial resolution is directly linked to the focal spot size. Therefore, achieving micrometer-scale resolution requires a micro-focus X-ray tube with a focal spot size of a few micrometers. However, such tubes operate at low output power (typically < 20 W), limiting X-ray flux and increasing acquisition time.

In this study, we adopt a scintillator-based optical magnification architecture that decouples the X-ray focal spot size from the spatial resolution. The key principle is that spatial resolution is determined primarily by:

- Scintillator thickness and light spread
- Optical lens numerical aperture (NA)
- Camera pixel size and quantum efficiency

rather than by geometric magnification alone.

Accordingly, a high-power X-ray tube with a relatively large focal spot can be used without degrading spatial resolution at the object plane. The significantly increased X-ray flux enables:

- Shorter exposure times
- Faster projection acquisition
- Reduced total 3D scan time

As a result, 3D imaging of HBM packages can be performed within minutes rather than tens of minutes, enabling compatibility with inline semiconductor inspection workflows.

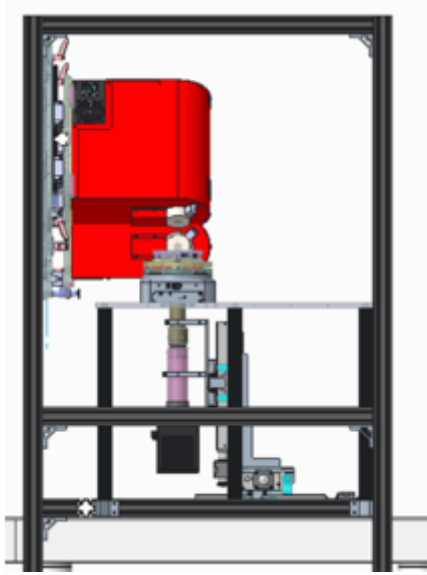


Fig. 1. The developed high-resolution X-ray 3D imaging system

3. Summary

In this study, we designed and developed a high-speed 3D X-ray inspection system tailored for HBM stacked memory packages. By adopting an optically coupled architecture, the spatial resolution was decoupled from the X-ray focal spot size, enabling the use of a high-power X-ray tube without sacrificing image quality.

The system achieved micrometer-scale resolution sufficient for TSV and micro-bump inspection while significantly reducing scan time compared to conventional geometric magnification systems.

Further improvements can be realized by:

- Employing higher light-yield scintillators
- Using optical lenses with larger numerical aperture (NA)
- Adopting high-quantum-efficiency CMOS cameras
- Integrating optimized reconstruction algorithms for semiconductor-specific structures

This approach provides a scalable solution for inline, high-throughput 3D inspection of next-generation HBM devices.

4. Further works

The developed high-resolution X-ray 3D imaging system is currently under active development. The following experimental validations and system improvements are planned:

System Performance Validation

The spatial resolution of the developed system will be quantitatively evaluated using standard resolution targets and slanted-edge MTF measurements. The system is designed to achieve a spatial resolution of less

than 1 μm , which will be experimentally verified through 3D reconstruction of dedicated resolution phantoms.

3D X-ray Imaging of HBM Packages

High-resolution 3D X-ray imaging of actual HBM stacked memory packages will be performed using the developed system. The 3D reconstructed volumes are expected to visualize internal structures including TSV arrays, micro-bump interconnections, and underfill layers with sub-micrometer spatial resolution, enabling reliable detection of defects in the 5–20 μm range.

Scan Time Benchmarking

The total 3D scan time of the proposed optically coupled system will be benchmarked against conventional micro-focus X-ray CT systems. The high-power X-ray tube employed in the proposed system is expected to significantly reduce the scan time, demonstrating the feasibility of inline inspection workflows compatible with HBM manufacturing throughput requirements.

Defect Detectability Assessment

The detectability of critical internal defects such as TSV voids, micro-bump misalignment, and delamination will be systematically evaluated using both phantom specimens and actual HBM devices. Detection sensitivity as a function of defect size and contrast will be characterized to establish the practical inspection capability of the system.

REFERENCES

- [1] WANG, Yuqing, et al. Recent progress on the recycling technology of Li-ion batteries. *Journal of Energy Chemistry*, 2021, 55: 391-419.
- [2] CARMIGNATO, Simone, et al. X-ray computed tomography. In: *Precision Metal Additive Manufacturing*. CRC Press, 2020. p. 313-346.
- [3] ESTRIBEAU, Magali; MAGNAN, Pierre. Fast MTF measurement of CMOS imagers using ISO 12333 slanted-edge methodology. In: *Detectors and Associated Signal Processing*. SPIE, 2004. p. 243-252.