NOVEL WORKFLOW FOR HIGH-RESOLUTION IMAGING OF STRUCTURES IN ADVANCED 3D AND FAN-OUT PACKAGES

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ABSTRACT

With the slowing of Moore's Law, advanced packaging technologies are needed to fill the performance gap that was previously satisfied by silicon device scaling. In many cases, these advanced packaging technologies use heterogeneous integration with 3D and fan-out technologies. In consequence, advanced analytical tools and techniques are needed. In this paper, we describe a novel approach for high-resolution cross-sectional imaging of advanced 3D package structures based on 3D X-ray microscopy (3D XRM) linked with a femtosecond-laser equipped FIB-SEM system. The capabilities of this workflow are demonstrated using a multichip package having stacked die, TSVs, Cu microbumps and flip chip interconnects.

ADVANCED 3D AND FAN-OUT PACKAGING

Chip scaling alone no longer provides the desired electrical performance. As a result, semiconductor package architecture and heterogeneous integration play a critical role to meet system requirements across diverse areas, including internet of things (IOT), 5G, high performance PC, mobile electronics, machine learning and artificial intelligence. In many cases advanced packages use 3D and fan-out wafer level technologies with fine-pitch interconnects such as Cu-pillar microbumps, through Si vias (TSV), and redistribution layers (RDL) [1]. Examples of advanced packages currently in production include:

- NAND packages having 16-high die stacks with 40um wire bond pitch
- DRAM cubes with TSV/micro-bumped die stacked 8-high
- MEMS and CMOS devices with a logic die bonded to a sensor die
- GPU modules with processor die and high bandwidth memory (HBM) cubes mounted on a 2.5D interposer
- Fan-out package-on-package (POP) with RDL and Cu pillars fabricated on reconstituted wafers

Defects in advanced packages can have a major impact on product cost, as there are many assembly process steps and there are often multiple die in a single package. Additionally, many defects can have latent effects, which may not be immediately detectable by electrical testing. As packages become more complex, traditional analytical workflows using acoustic microscopy, 2D X-ray, and mechanical cross-sections often struggle to provide data for process characterization and problem resolution [2].

This has driven industry-wide adoption of 3D analysis techniques, and 3D XRM has become an industry standard for non-destructive analysis of advanced packages [3]. After XRM imaging, it may be necessary to leverage the contrast and resolution advantages of the scanning electron microscope (SEM). Since cross-section techniques are challenged in results quality and throughput by the shrinking structures enabling fine-pitch high density interconnect, and material volumes involved in typical packages are too large for efficient focused ion beam (FIB) processing, improved workflows pairing non-destructive and destructive analysis are required.

LINKED ANALYTICAL WORKFLOW

While the number of package layers and complexity increases, package interconnects evolve further towards ever-smaller dimensions. For example, Cu-pillar microbumps below 10 µm diameter have been demonstrated [5]. A key analytical technology for these small structures is submicron 3D XRM, wherein a series of 2D x-ray projection images are mathematically reconstructed into a 3D image enabling visualization of the inner structures of an intact device, non-destructively [3, 7]. State-of-the-art 3D XRM has a spatial resolution of 500 nm with voxel sizes of 40 nm [4]. Imaging at higher resolutions becomes necessary as interconnects and defects continue to scale downwards in size. Furthermore, with the automotive industry now pursuing defect levels of near zero defective parts per billion, it is vital to be able to conduct in-depth analyses of complex internal package structures.

A novel workflow (Fig. 1) combining submicron 3D XRM and FIB-SEM imaging was developed to enable higher throughput for nanoscale-resolution imaging at desired package locations as a routine method. The missing link between these techniques was a sample preparation method allowing easy, fast and accurate access to a typically buried region of interest (ROI) previously imaged by XRM. To enable this, we have equipped a FIB-SEM system with a femtosecond (fs)-laser for precise material removal and rapid access to a targeted structure for high-resolution cross-sectional imaging.

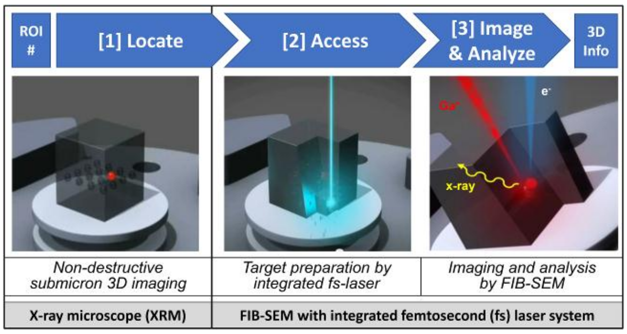

Figure 1: Schematics of the correlative workflow combining 3D XRM (step1), femtosecond laser preparation (step 2), FIB polishing and SEM imaging and analysis (step 3).

CASE STUDY

A case study was conducted using a GLOBALFOUNDRIES 14 nm 3D TSV multi-chip test vehicle [6], summarized by correlative images in Figs. 2a, 2b, 2c and 3. The study focused on the Cu-pillar microbumps, which are 25 µm in diameter and connected to C4 bumps by TSVs. The layer containing the Cu-pillar microbumps is located 720 µm below the top surface of the package. With guidance from the XRM images, the fs-laser was used to open a 300 x 200 μm^2 area with an overall depth of 1.7 mm.

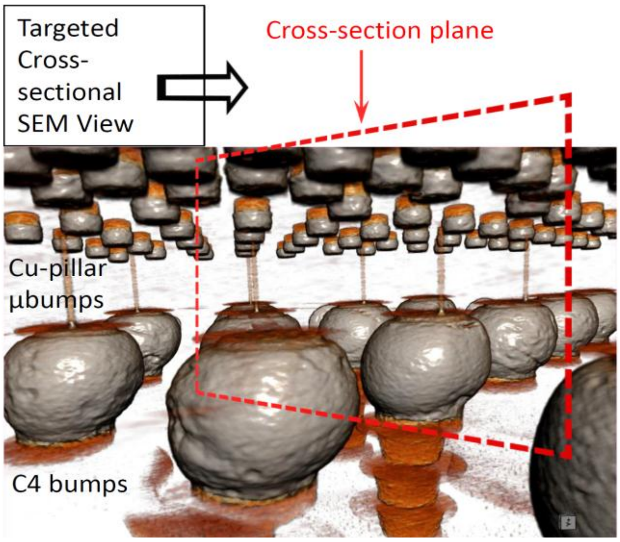

Figure 2a: 3D XRM image of package interconnect consisting of Cu-pillar microbumps and C4 bumps.

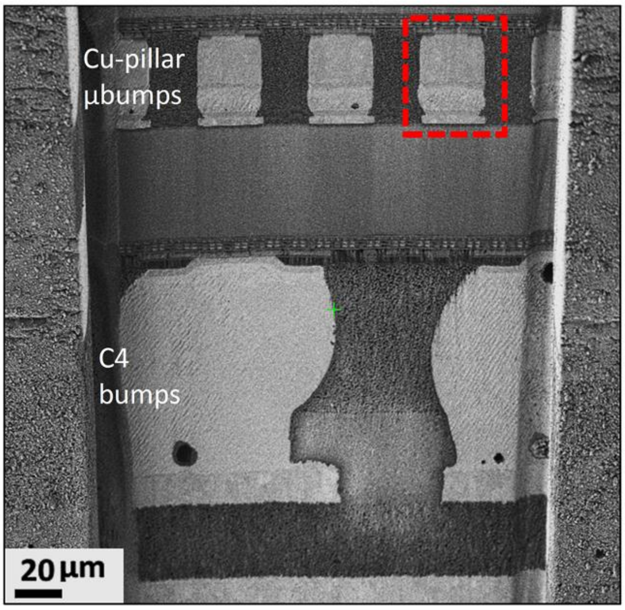

Figure 2b: Backscattered electron SEM image of package interconnect consisting of Cu-pillar microbumps and C4 bumps, immediately after laser processing and correlating to the area defined in Fig. 2a. Scale bar: 20 µm.

During cutting, the fs-laser causes formation of laser-induced periodic surface structures (LIPSS) and a small heat-affected zone (HAZ). These artifacts are largely confined to the surface of the laser-cut face, and re-deposition of ablated material is minimal. Thus, it is possible to directly view a significant amount of structure immediately after fs-laser cutting. As shown in Fig. 2b, details of the microbump and even the back-end-of-line (BEOL) interconnects are visible in the SEM without a requirement for FIB polishing. In general, compared to nanosecond [8] or continuous wave laser preparation, fs-laser pulses induce significantly less collateral damage to adjacent structures. For this 3D TSV multichip package, a very shallow heat-affected zone (HAZ) of <1 µm was measured at the sidewall, where the laser beam impinged normal to the sample surface.

For detailed study of intermetallic compounds (IMC) and grain structures, a FIB polishing step using gallium ions removed the LIPSS and HAZ-affected material, with results shown in Fig. 2c. Backscattered electron images of a laser-cut microbump are compared before (Fig. 3a) and after (Fig. 3b) this additional polishing step. Many features and layer details are already visible immediately after cross-sectional laser preparation, and the FIB polish enables high-resolution imaging of the IMC. Thus, a fast workflow for analysis of stacked die interconnects has been shown, with first images possible in less than 30 minutes after identification of the ROI by XRM imaging. This workflow enables routine high-resolution cross-sectional imaging of buried interconnects in practical timeframes to aid package development, yield optimization and failure analysis.

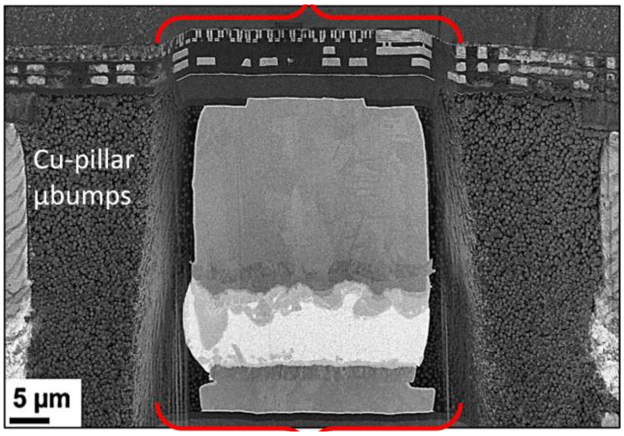

Figure 2c: Backscattered electron SEM image of Cu-pillar microbump (outlined in Fig. 2b) after Ga-FIB polish. Scale bar: 5 µm.

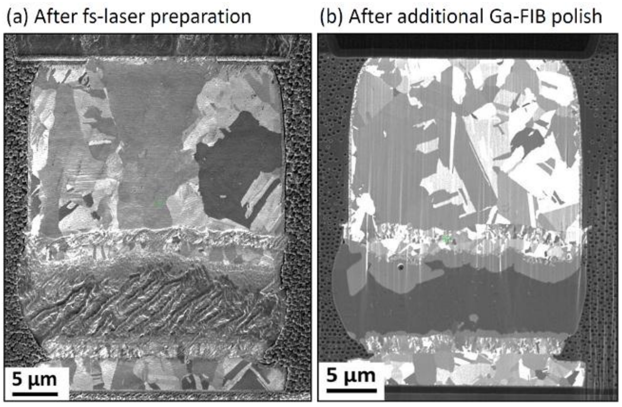

Figure 3: FIB secondary electron image series comparing the cross-section quality directly after fs- laser processing (a) and after an additional Ga-FIB polish step (b). Scale bars: 5 µm.

SUMMARY

The authors described a novel correlative workflow combining submicron 3D XRM and high-resolution FIB-SEM. A case study was conducted with this workflow using a 3D TSV multichip package. Results and conclusions from the case study were presented, demonstrating the usefulness of the new workflow. Further, by using fs-pulsed laser preparation, concomitant debris and damage to sample structures are significantly reduced compared to nano [8] - and picosecond-laser based ablation. The predominantly athermal interactions of fs-laser processing achieve smooth cuts without the ejection of molten material, enabling clean large-scale cross-sections. This is confirmed also by previous studies, e.g. [9-10]. As demonstrated, defects like voids, solder shorts and interconnect cracks could be imaged over millimeters of area immediately after laser preparation. Further, the direct visibility of features and layers within the laser-cut region enables an optimized site-specific Ga-FIB post-polishing process, avoiding the necessity for broad post-processing. The surface-confined LIPSS and HAZ damage, combined with minimum re-deposition and rapid identification of areas for follow-up polish significantly reduce the FIB-based post-polishing time for artifact-free analysis. The presented solution offers unmatched time-to-results for rapid cross-sectional package interconnect analysis at high-resolution.

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REFERENCES

[1] R. Beica, "The growth of advanced packaging. What makes it so special?" presented at the *Advanced Semiconductor Technology Conference (ASTC)*, 2015.

[2] I. De Wolf et al., "Expected Failures in 3-D Technology and Related Failure Analysis Challenges," *IEEE T. Comp. Pack. Man.*, vol. 8, 2018, pp. 711-718.

[3] C. Hartfield et al., "From PCB to BEOL: 3D X-Ray Microscopy for Advanced Semiconductor Packaging," in *International Physics of Failure Analysis (IPFA)*, Singapore, 2018.

[4] ZEISS Xradia 600-Series Versa, Submicron X-ray Imaging, Product Information V1.0

[5] J. Oswald et al., "2.5D packaging solution - from concept to platform qualification", in *17th Electronics Packaging Technology Conference (EPTC)*, 2015, pp.1-7

[6] R. Agarwal et al., "3D Packaging Challenges for High-End Applications," in *2017 IEEE 67th Electronic Components and Technology Conference (ECTC)*, 2017, pp. 1249-1256

[7] C. Schmidt, "3-D X-ray imaging with nanometer resolution for advanced semiconductor packaging FA," *IEEE T. Comp. Pack. Man.*, vol. 8, 2018, pp. 745-749.

[8] H. Stegmann, "Flexible interconnect viewing", *Solar Magazine*, 2012, pp. 22-27.

[9] M. J. Pfeifenberger et al., „The use of femtosecond laser ablation as a novel tool for rapid micro-mechanical sample preparation," *Materials and Design*, vol. 121, 2017, pp. 109–118.

[10] K. Sugioka, Y. Cheng, "Ultrafast lasers - reliable tools for advanced materials processing," *Light-Sci. Appl.*, vol. 3, 2014, pp. 1-12.