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Targeted Sample Preparation and Analysis of Advanced Packaging using Correlated X-ray Microscopy and Laser FIB

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Abstract

X-ray microscopy and femtosecond (fs) laser integrated FIB-SEM are combined in a workflow to guide precise and targeted sample preparation to enable functional testing and fault isolation without damaging the package and IC.

Introduction

Emerging technologies such as AI, 5G, IoT, wearables, cloud, computing, and autonomous vehicles hold great promise for improvement and transformation of human lives globally. In today's More-than-Moore era, advanced packaging has emerged as a critical enabler for these next generation of electronic devices. System level performance improvements through heterogeneous integration has added more functionality while improving the cost-performance gaps. Developments in various materials, processes, and architectures for 2.5D and 3D packaging has enabled high density interconnects with shrinking dimensions and pitch which is essential for continued scaling in performance and integration of various devices at lower costs.

As the complexity of electronic packages continues to increase, so do the challenges in characterization during process development and failure analysis (FA). Traditionally, FA workflow in IC packaging begins with the electrical and functional testing of the device followed by incoming optical and 2D X-ray inspection. Subsequent fault isolation using multiple tools and techniques have become necessary starting with curve tracing, TDR, high resolution, non-destructive imaging using SAM, X-ray CT, and IR imaging followed by physical analysis using mechanical and focused ion beam (FIB)-based cross-sectioning for visualizing and characterization of defects, Figure 1. [1]

Once the fault isolation is completed and a failure site has been localized, high-resolution imaging techniques such as 3D X-ray microscopy (XRM) can visualize defects and guide sample preparation for physical analysis to disclose defects for root cause investigation [2, 3]. However, the region of interest (ROI) may be several hundreds of microns (μm) or millimeter (mm) deep into the package which requires removal of large volume of material with high accuracy in the microns or better range. Conventional techniques such as mechanical cross-section enable large cross-section preparation but are slow and have limited accuracy. FIB using liquid metal ion source or plasma ion source is very precise and effective in preparing cross-sections in the hundreds of microns cubic volume which would still need long preparation times to access deep structures (hours to days). Laser ablation using ultra-fast pulsed lasers have been adopted as stand-alone and integrated into FIB systems which allows large volume removal (mm^3) at high throughput (minutes to hours) [4-7].

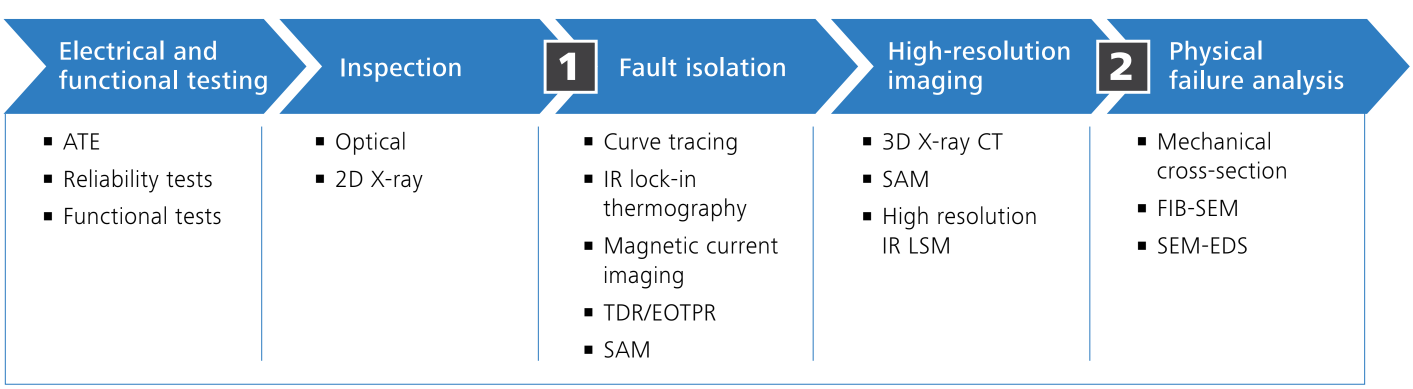

Figure 1 *IC package FA workflow with sample preparation steps at 1 and 2*

For targeting sub-surface and buried features, an XRM-guided workflow for sample preparation through integrated laserFIBs has already demonstrated high precision and high throughput sample preparation in 2.5D packaging and display [8-11]. Besides large volume removal, the ability to access deeply buried structures with high precision can also be used to selectively sever electrical wires and connections to simplify and isolate complex circuitry during fault isolation.

In advanced packages with high IO and complex interconnect structures, localization of tiny defects by electrical curve tracing, TDR, or lock-in thermography can be challenging. Finding these failures in complex packages such as system-in-package, multi-stack dies and package-on-package devices with several functional components can be quite time consuming. Deduction by elimination would require disconnecting or breaking the electrical connectivity in parts of the circuitry without affecting any other component which can be a challenge. This would require a precise and selective technique to break the interconnects and wires while retaining all other functionalities of the device.

In this work, we apply a workflow combining a non-destructive 3D X-ray microscopy that guides the sample preparation using a FIB integrated with an fs laser with high precision for fault isolation in 3D packages.

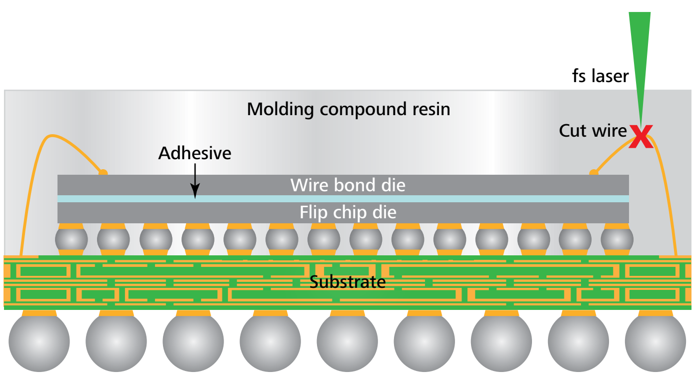

Figure 2 *Schematic illustrating how wire bond can be cut to isolate functions from the top die during functional testing and fault isolation*

Methods

A. Sample Preparation

For the demonstration of this workflow, we extracted a base band modem IC from the motherboard of a mobile phone, which is a 3D package consisting of one flip-chip die (baseband processor) connected to the substrate through solder bumps and another die (memory and/or analog) with wire bonds. Upon preliminary inspection, no damage to the internal structures was observed.

B. Workflow

In 3D packages, electrical connections going to the different modules may have complex circuitry that could lead to challenging fault isolation routines to identify the failure sites. In such 3D packaging, it would require deactivating certain features or parts of the circuit to isolate some components and determine failure sites with higher accuracy. The ability to selectively break an interconnect or wire without damaging the chip for functional testing can be achieved if they are accessible either through the molding compound or through other protective packaging materials as highlighted in Figure 2.

The workflow combines two techniques, a high-resolution non-destructive 3D X-ray microscopy and an fs laser integrated FIB-SEM. In this work, we utilize ZEISS 620 Xradia Versa and ZEISS Crossbeam laser 550 to perform the analysis. Figure 3 illustrates the process and steps involved. The sample is scanned at low resolution to obtain an overview of the entire package and interconnect structure to check for defects or anomalies. This information may be available from other fault isolation techniques or known data and may be skipped. Once the region of interest (ROI) is identified, this must be referenced to a unique feature that is visible and accessible for imaging either by SEM or optical methods on the surface. Hence, the top surface above the ROI is marked to add fiducials for easy reference to the sub-surface feature. The package is scanned again using the X-ray microscope at sufficient resolution to capture both ROI and the surface fiducials to localize the ROI with respect to the surface fiducials.

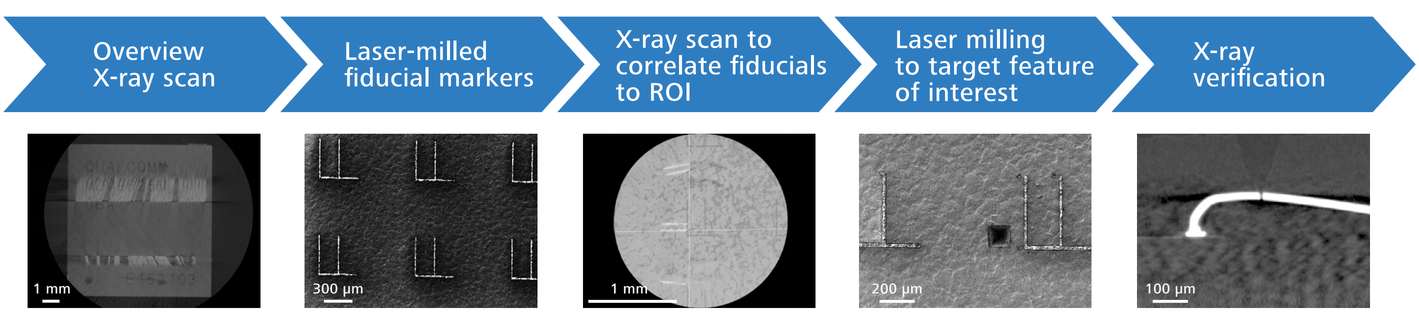

Figure 3 *Sample preparation workflow process using 3D X-ray guided laser milling of interconnects for fault isolation*

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Subsequently, the fs laser is used to perform a precise fine cut on the desired wire or interconnect to isolate features or parts of the circuitry. The sample is again checked using the X-ray to determine if the precise cutting is sufficient or successful for further fault isolation.

In this example we demonstrate that the 20 μm wide wire that is 150 μm deep can be precisely cut with the laser without decapsulating or damaging any part of the die and other interconnects or neighboring wires. To improve the laser milling accuracy, a calibration step is performed to determine the parameters for accurate positioning and laser milling depth. Once the calibration is performed, the laser parameters can be replicated on additional wires or on other samples made of similar materials. The results are presented in the next section.

Results

The first experiment is performed to determine the optimal milling parameters, Figure 4. The second experiment is performed targeting a single wire to demonstrate precision and replication of the milling parameters on other sites, Figure 5. The overview X-ray scan is acquired in 28 minutes at 100kV, 14W and 12 μm/voxel. The low-resolution fast scan is sufficient to observe the internal structure of the devices and layout of the interconnects and wires. The sample is mounted on a carbon stub which allows transfer of the sample between the XRM and LaserFIB. Subsequently, the sample is transferred to the LaserFIB to generate fiducial markers on the top right. The Crossbeam laser 550 operates with a separate chamber for laser milling and has micron scale accuracy with a registration process between the SEM and laser. The laser milling is performed at 4W with a pulse frequency of 10 KHz and milling time is 1 second. The fiducial markers are 20 μm wide and over 1.2 mm x 1.2 mm. The sample is scanned again with the XRM at higher resolution at 2 μm/voxel at 100kV and 14W in 2 hours.

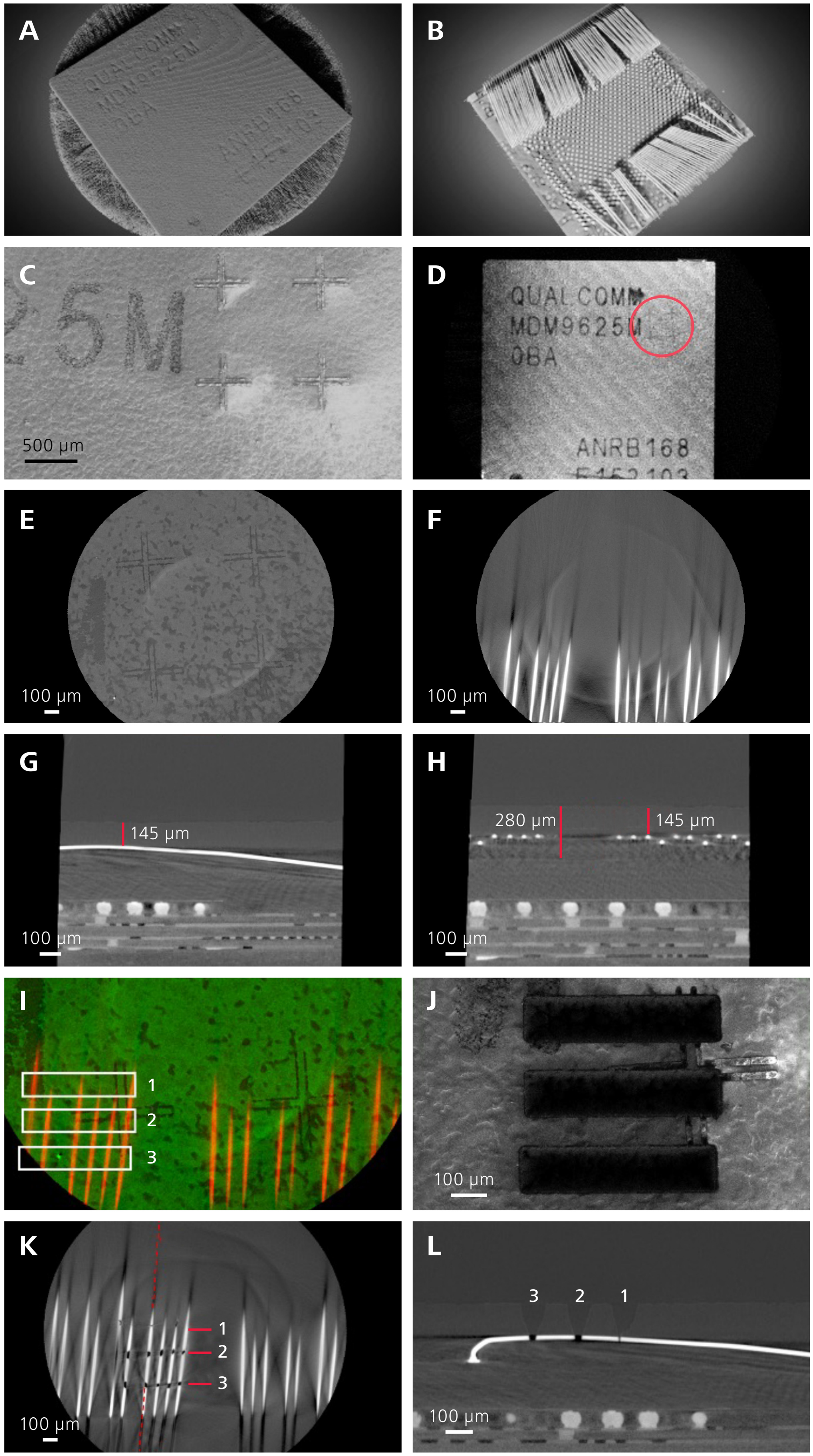

Figure 4 A) Overview X-ray scan of chip showing top molding compound surface and B) internal wires and flip chip bumps. C) SEM image after laser marking of fiducials. D) XRM overview showing position of fiducials highlighted by red circle. E) Higher magnification XRM scan virtual cross-section of the fiducials and F) underlying wires. G) and H) Distance of the wires and chip from the top surface is measured to be 145 μm and 280 μm respectively. I) Top surface (in green) with laser fiducuals is overlayed with wires (in orange) and the position of laser milling test patterns 1,2 and 3 with varying doses are shown. J) SEM image after laser milling. K) XRM scan showing virtual cross-section on top of the wire and L) virtual cross-section view of wires cut corresponding to the 3.

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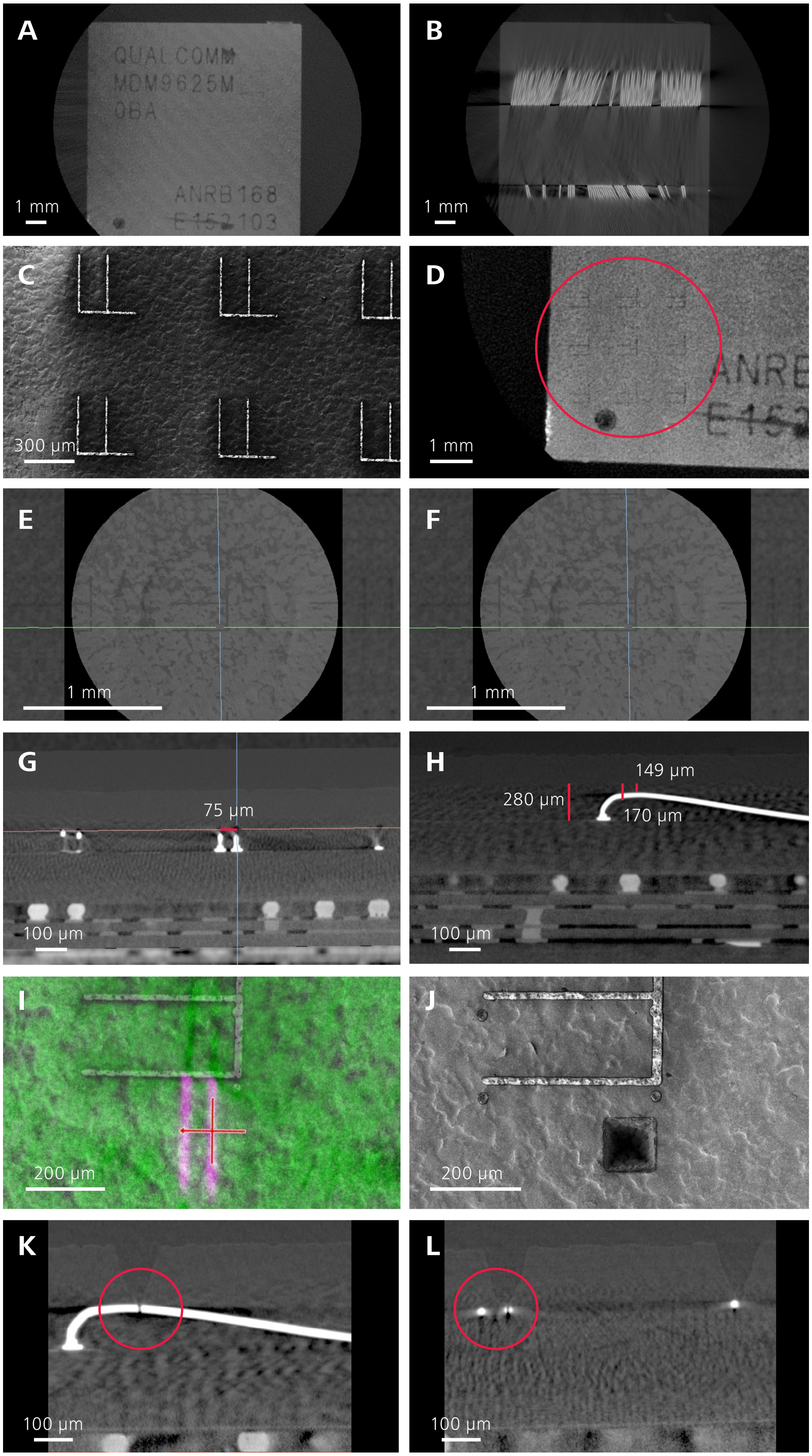

Figure 5 *A) Overview X-ray scan of chip showing top molding compound surface and B) internal wires and flip chip bumps. C) SEM image after laser marking of fiducials. D) XRM overview showing position of fiducials. E) Higher magnification XRM scan virtual cross-section of fiducials and F) underlying wires. G) The distance of wire from neighboring wire and H) distance of wire from top surface and distance of chip from the top is measured to be 149 µm and 280 µm respectively. I) top surface (in green) with laser fiducuals is overlayed with the wires (in pink) and the position of laser milling is highlighted by the crosshair. J) SEM image after laser milling 100 x 100 µm square targeting 150 µm deep wire. K) XRM scan showing virtual side view of cut wire while L) maintaining neighboring wire.*

Now both the ROI and fiducial markers are captured. The position of the wires with respect to the laser milled surface fiducial markers can be determined by overlaying the two virtual cross-sections. The wire is 145 µm below the surface and has a diameter of about 20 µm. The die is 280 µm below the surface giving a clearance of about 115 µm from the bottom of the wire. Since the material information is not known, the laser milling parameters are to be optimized with a dose test such that the milling only cuts the wire and does not penetrate deeper to damage the die. A series of rectangles (labelled 1, 2 and 3) 100 µm x 100 µm is milled at 4W with a frequency of 10 KHz and speed of 20 mm/sec while varying additional parameters to control the milling depth to determine the optimal conditions for the laser milling. The milling pattern cuts multiple wires providing several data points to check for repeatability and local variations in the materials due to fillers or additional components. The milling takes less than 20 seconds to complete. The sample is then scanned again in the XRM at 2 µm/voxel at 100kV and 14W in 2 hours to check the depth of the laser cuts. It can be observed that the dose in rectangle 1 is insufficient to cut the wire reliably while the dose in rectangles 2 and 3 cut the wires and do not damage the die below. The optimal dose is chosen to be dose 2.

The same workflow is now followed to target a single wire in another area of the chip as shown in Figure 5. Previous X-ray overview scans provide low resolution position information to laser mill surface fiducial marks on the lower left corner of the chip. Laser milling of fiducials follow earlier recipe and are completed in less than 1 second. Higher resolution X-ray scan at 2 µm/voxel is required to obtain accurate positioning of the target wire. The wire is about 150 µm from the top surface and the nearest wire is at a pitch of 75 µm. The overlay of the X-ray image with the fiducials and wires are aligned with the SEM image to provide a precise location of the wire, Figure 5I.

Now a 100 µm x 100 µm rectangle is positioned precisely and milled with the laser following the earlier recipe. The milling is completed within 20 seconds. The final X-ray scan verifies that the laser cut precisely targets the wire of interest and doesn't damage the neighboring wire or the die below indicating the workflow can be employed for precise and targeted sample preparation.

Discussion

In this work, the recipe is repeatable at different locations within the same sample and for similar packages using the same molding compound materials. However, the variations arising due to the presence of filler materials and other additives are not thoroughly studied and would need further optimization. The gaussian profile of the laser beam introduces a side wall taper of close to 15 degrees which adds requirements on the minimum opening area at the top surface to completely cut the wire and this depends on the depth of the interconnect from the surface. The entire workflow takes 5 hours and can be completed in 6-8 hours including data reconstruction and preparation time in between steps. Further functional testing of the chip is required to validate the proposed method and is part of the future work.

Conclusion

A novel correlative workflow using LaserFIB and 3D XRM techniques is presented for targeted sample preparation for fault isolation in 3D BGA packages consisting of wire bonds and flip chip devices. The case study presented targets an interconnect wire connecting the top die in the 3D package to isolate part of the circuit / device for functional testing and fault isolation. The 620 Versa 3D XRM was used to scan and identify the interconnects and features and correlate with surface features patterned on the sample using the Crossbeam 550 fs-Laser FIB-SEM for precise targeting and sample preparation. The wire was cut precisely without damaging neighboring wires or the die while retaining most of the package for further testing. The entire process from feature identification until the wire milling and isolation of the circuit is completed in 8 hours highlighting the throughput and precision capabilities of this streamlined workflow which can open new capabilities in the fault isolation and failure analysis of advanced packages.

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