Pairing Laser Ablation and Xe Plasma FIB-SEM: An approach for precise end-pointing in large-scale Physical Failure Analysis in the Semiconductor Industry

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Abstract

In this work we present a large-volume workflow for fast failure analysis of microelectronic devices that combines a stand-alone ps-laser ablation tool with a SEM/Xe Plasma FIB system. In this synergy, the ps-laser is used to quickly remove large volumes of bulk material while the SEM/Xe Plasma FIB is used for precise end-pointing to the feature of interest and fine surface polishing after laser. The concept of having a stand-alone laser tool obeys the logic of maximizing productivity as both systems can work simultaneously and continuously. As application examples we first present a full workflow to prepare an artefact-free, delamination-free cross-section in an AMOLED mobile display. We also present applications examples that require cm-sized long cuts to cut through whole microelectronic devices, or removal of cubic-mm of material to prepare mm-sized cross-sections in packages. We discuss a way how to implement correlation data across the laser and FIB-SEM platforms through SYNOPSYS Avalon SW allowing precise navigation to the area of interest using layout circuit overlays. We also show an example of image bitmap overlay to navigate across platforms and end-pointing.

Introduction

Physical Failure Analysis (PFA) is routinely used in the semiconductor industry for finding root-cause failure in electronic components. PFA is helpful in investigating defects in mobile displays (Organic Light-Emitting Diode (OLED), Active Matrix-OLED (AMOLED)), Flip-Chip Packages, High-Bandwidth Memory (HBM) chips, Through-Silicon-Vias (TSVs), Micro Electro-Mechanical Systems (MEMS) and other microelectronic components. Examples of defects would include cracks, voids, bad contacts, delamination, underfilled vias, etc, all these causing malfunctioning of these devices.

A standard approach in PFA is implemented through sample cross-sectioning. In this way, structures located at different depth planes become accessible for their detailed inspection and analysis using diverse techniques such as SEM imaging and EDS or EBSD microanalysis. Cross-sectioning is particularly useful when the regions of interest (RoI) are located hundreds of microns or even a few millimetres below the surface of the samples. This is precisely the case of the above-mentioned devices. However, making accessible the entire surface of such deep cross-sections for subsequent inspection requires inevitably on the one hand removing large volumes of material of the order of cubic millimetres and on the other hand precise end-pointing.

Historically, these tasks have been performed by mechanical sawing, mechanical polishing, and broad ion beam polishing. Due to the increasing complexity and sensitivity of microelectronic structures, other techniques such as Focused Ion Beam (FIB) have been instead adopted because of superior capabilities for highly localized sample preparation, and precise end-pointing. Besides, no mechanical stress is induced by FIB. FIB technology has progressed to the point of developing Xe Plasma FIB capable of 3 µA[1] making it possible to cope up until now with such demanding sample preparation tasks.

However, the ever-increasing world's demand for electronic devices, their miniaturization, and advanced integration constantly urges to obtain higher volume yields and shorter time-to-result analytical methods without compromising quality. It is clear that aiming at satisfying such dynamic and challenging needs cannot rely on Xe Plasma FIB only but new approaches for faster and more effective large-volume failure analysis workflows need to be conceived.

[1] The TESCAN Xe Plasma FIB-SEM systems are equipped with the iFIB+ column capable of reaching FIB currents up to 3 µA.

With that in mind, in this work we present a large-volume workflow [1, 2] for fast failure analysis of microelectronic devices that combines a stand-alone ps-laser [3, 4] ablation tool with a Xe Plasma FIB-SEM system. In this synergy, the ps-laser is used to quickly remove large volumes of bulk material while the Xe Plasma FIB-SEM is used for fine surface polishing after laser processing with precise end-pointing capability to reach and stop at the feature of interest. The concept of having a stand-alone laser tool obeys the logic of maximizing productivity as both systems can work simultaneously and continuously**.** This workflow has been conceived to profit from the key advantages of two technologies that have been specifically designed for large volume material removal and create a unique synergy for rapid mm-scale sample preparation needed in failure analysis labs. Furthermore, the present workflow can well fit into broader PFA workflows that include other standard FA tools.

As a proof concept, in this work we present concrete examples of large-volume workflows applied in sample preparation for failure analysis of microelectronic devices. As a first example we present a full workflow that enables mm-sized sample extraction by laser from whole AMOLED displays as a first step followed by a laser cut using a novel oblique geometry that allows clear FIB/SEM top-view identification of specific depth planes. Thus, local polishing of wide sections of the TFT layers with Xe Plasma FIB can be optimized for better quality and, overall FIB polishing time be dramatically reduced. Is to be stressed that no delamination of the display occurs thanks to the fine-tuned gentle sample processing recipe (see Figs. 1 and 2).

We show the capability to perform cm-sized cuts. As a concrete example we cut across a stacked memory chip. Since both laser as well as Xe Plasma FIB tools are equipped with tilt-capable sample stage, the cut can be performed with taper angle correction to have a straight wall at the cut face. This long cut enables inspection of different regions/layers of the package and the region of interest can be gently polished with Xe Plasma FIB for detailed ultra-high-resolution SEM inspection. See Fig. 3. The process can be also set to keep the edges of the samples untouched, so to avoid any possible inherent packaging-related stress release – delamination. As an additional example for sample preparation, we show a 1-mm cross-section in a flip-chip package using laser ablation to prepare the bulk trench and the Xe Plasma FIB for final polishing, Fig. 4.

By making fully compatible the CAD-assisted navigation SYNOPSYS Avalon SW on both laser and FIB platforms, it is possible to intuitively correlate both systems, and implement easy navigation across sample and precise end-pointing. We show a concrete example of this functionality in a workflow, see Fig. 5. The use of GDS-assisted navigation simplifies finding the RoI previously processed by laser for further postprocessing with Xe Plasma FIB. An example of image bitmap overlay to navigate across platforms and end-pointing is also presented in this work, Fig 6.

Instrumentation

The workflow described in this work is based on pairing two stand-alone technologies that have been specifically designed for large-scale material removal, namely a ps-laser (3D-Micromac microPREP™ PRO) and high-speed milling Xe Plasma FIB-SEM (TESCAN SOLARIS X). The main advantages of this workflow concept can be described as follow:

- Productivity is maximized as both systems can work simultaneously and continuously as opposed to platforms where laser and FIB-SEM are integrated into a single chamber.
- Stand-alone approach protects the FIB-SEM chamber against ablated material contamination and cross contamination of samples.
- Laser chamber can accommodate large samples such as whole mobile displays or sections of wafers for their sectioning or die extraction.
- A broad range of microanalytical techniques can be implemented through the FIB-SEM chamber (i.e., EDS, EBSD, TOF-SIMS).
- Synergies of multi-tool setup in the FA labs allows multi-modal correlations.
- The laser is fitted with a sample stage with forward-tilt enabling:
- Taper angle[2] correction for straight walls at cross-sections – which is beneficial when preparing cross-sections that are several hundreds of microns or even a few millimeters deep. This shortens final FIB cleaning and end-pointing time and allows flexibility in shapes which is beneficial for 3D and micro-CT specimen preparation.
- Laser cuts with oblique geometries with fully controllable inclination angle (as opposed to that created by laser taper angle) – oblique laser cuts make possible to FIB-SEM view and identify from top specific regions at different depth planes which in turn enables local Xe Plasma FIB polishing.
- CAD navigation SW (SYNOPSYS Avalon) on both laser and FIB platforms for intuitive correlation between them, easy navigation across sample and precise end-pointing tool, see Fig. 5.
- CAD files can be also used for preparing customized laser cuts (i.e., frames for sample extraction from whole specimen, die extraction from piece of wafers, etc.) or multilayer-multirecipe processes.
- Bitmap image overlays can be loaded into the system. The images can be for instance those generated from other analytical instruments such as optical and infrared microscopes, micro-CT, thermal emission maps, etc. Such overlays are used to easy navigate across the sample to the region of interest or defects to be isolated, see Fig. 6.

[2] Taper angle is an inherent characteristic of all focused beams with Gaussian beam profile.

Results – Application Examples

AMOLED Display – sample preparation

PFA of AMOLED displays is a challenging analytical task where pairing ps-laser ablation and Xe Plasma FIB is a clear application in which the time for accessing regions of interest can be reduced dramatically. The common target of interest in AMOLED displays is the TFT layers which is sandwiched by different layers including a thick glass substrate and organic light-emitting active layers. Accessing the TFT layer necessary requires preparing cross-sections that are hundreds of microns deep, a task that is extremely challenging and time-consuming – if not unpractical – even for Xe Plasma FIB alone.

Figure 1. Workflow for large-volume processing and preparation of AMOLED display samples for PFA. Laser processing steps. (1a) Whole AMOLED display[3] to be analyzed. (1b) A 2 cm × 2 cm sample extracted from the whole display using ps-laser. This step is intended to isolate the failure at the region of interest[4] and it also makes easier handling the sample during laser ablation and FIB processing[5]. (1c) Detail of one of the side walls of the sample showing no delamination and negligible debris. (1d) Cross-section with purposely oblique geometry prepared at the edge of the sample. The angle of the oblique cut is fully controllable thanks to the working angle function enabled by the tilting-capable motorized stage. A laser cut geometry allows FIB-SEM top view for clear identification of different depth planes in the display enabling local FIB polishing of wide sections of the TFT layer for subsequent ultra-high-resolution SEM inspection. This provides an effective and clearly timesaving alternative to top-down FIB polishing which is very time-consuming since low currents need to be used to avoid damaging highly sensitive layers present in AMOLED displays.

Mechanical methods to cut or cleave AMOLED displays induce extensive damage such as stress and delamination that complicates or makes failure analysis deceiving or unfeasible [5]. Nanosecond laser cutting produces an extensive heat affected zone (HAZ) and debris which prevents further sample analysis. Ultra-short pulse laser ablation (USPLA) is a prominent analytical technique envisaged to enable ultra-fast sputtering rates with minimal HAZ [6, 7].

The workflow using ultra-short pulse laser presented in this work allows cutting out and extracting mm-size samples from whole AMOLED displays and preparing large bulk trenches using an innovative laser cut with oblique geometry. With the right laser parameters, mechanical stress or swelling caused by laser is negligible and therefore no delamination is induced. Thanks to the oblique laser cut, it is possible to clearly identify from top SEM/FIB view the TFT layer, and therefore sections of up to 1 mm wide of this active layer can be gently polished with Xe Plasma FIB and subsequently specific RoI be inspected with ultra-high-resolution SEM imaging. In this way, the deeply buried TFT structures can be quickly accessed for site-specific examination. Concretely and as an example, using the present workflow, the total time for preparing a 2.5 mm-wide laser oblique bulk trench followed by a local fine polishing of a 500 µm-wide section of the TFT layer with Xe Plasma FIB is about 2 hours. See Figs. 1 and 2. The use of laser represents a dramatic reduction in sample preparation time[6] when compared to the time that would take to complete a 500 µm-wide cross-section using Xe Plasma FIB only[7].

[3] Commercial Samsung Galaxy S7 with super AMOLED display.

[4] Extraction of samples or dies from different microelectronic devices using this workflow is possible. For instance, HBM dies can be extracted or cut out from whole packages for their individual processing and analysis.

[5] CAD navigation SW (SYNOPSYS Avalon) has been made compatible with the SW interface on both laser and FIB platforms for intuitive correlation of both platforms, easy navigation across sample and precise end-pointing tool. The workflow using this functionality is also described in this paper.

[6] It is also important to mention that such long FIB processes at such high currents consumes a great deal of the used aperture lifetime. In the case of Xe Plasma FIB systems that are routinely used for such applications downtime dedicated for aperture exchange would also be reduced dramatically.

[7] Attempting to prepare only a bulk trench of size 500 µm × 500 µm × 450 µm (wide/height/depth) with Xe Plasma FIB would take over 16 hours at maximum FIB current of 3 µA – estimated time based on the milling rate of Xe ions on Si: 0.37 µm³/nC (sputters rates at 30 keV, normal incidence on Si calculated from SRIM [8, 9]).

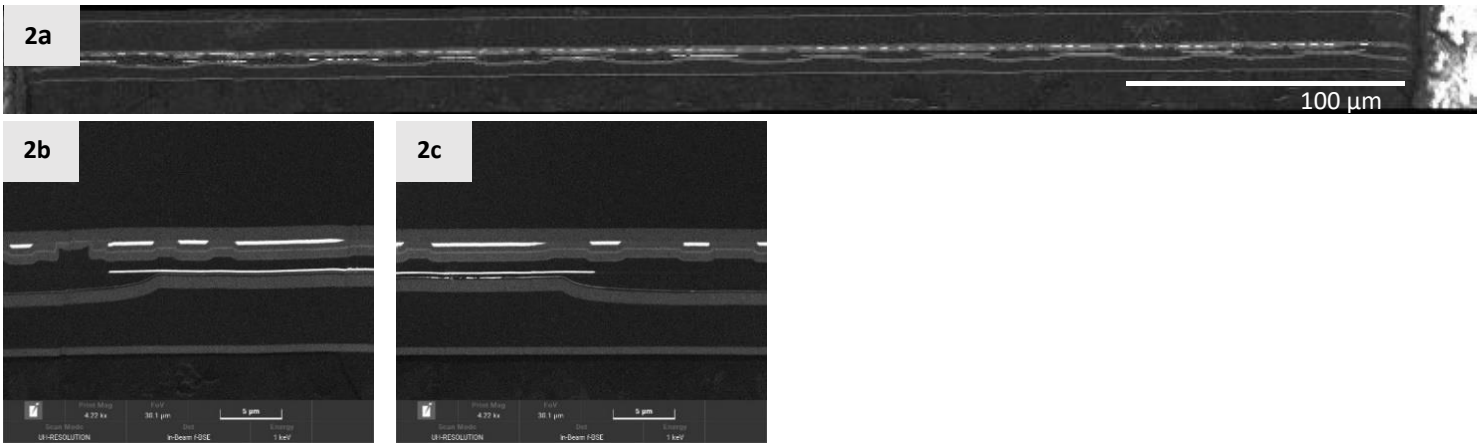

Figure 2. Workflow for large-volume sample processing and preparation of AMOLED displays for PFA. Xe Plasma FIB polishing. The oblique cut implemented with ps-laser combined with Xe Plasma FIB enable easy local polishing at specific depths in AMOLED displays. In this way, wide sections of hundreds of microns of the TFT layer become accessible for ultra-high-resolution SEM inspection and failure analysis. We emphasize that there is no delamination induced during this workflow. (2a) High resolution stitched-panoramic SEM overview image of a 500 µm wide cross-section at the TFT layer[8] (2b, 2c) Detail SEM images showing selected metal contact structures at the TFT layer.

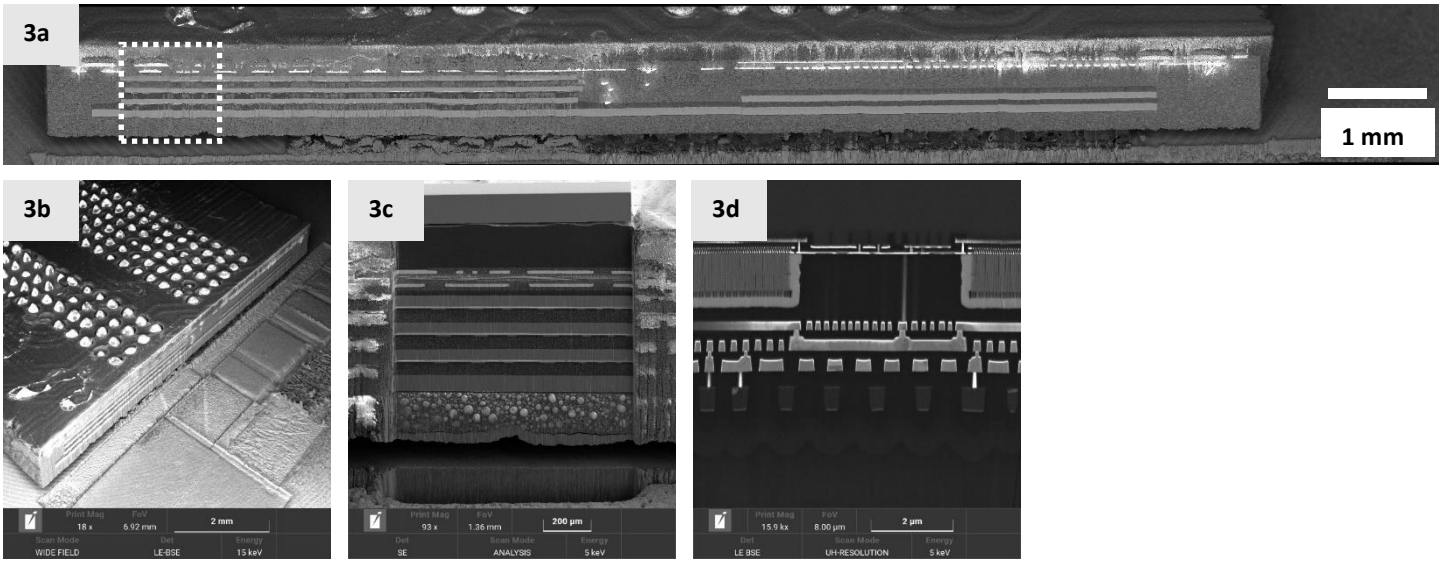

Figure 3. Workflow for large-volume sample processing and preparation of memory stack chips for PFA. Memory stacked chip cut along the full length of one of its sides using ps-laser. (3a) Stitched SEM image showing the 12-mm wide cross-section cut exposing all layers and structure of the chip on the selected direction. The quality cut and minimal debris allows identification of layers of the chip right after laser processing. The surface is ready for – if needed – local top-down fine polishing with Xe Plasma FIB at specific sections containing areas of interest for further ultra-high-resolution SEM inspection. (3b) Taper angle correction is possible during laser processing resulting in straight walls on the entire cross-section. (3c) 1-mm cross-section of a selected part of the chip (indicated with a white dotted frame in Fig. 3a after Xe Plasma FIB polishing at 3 µA using a 1-mm Si mask (TRUE X-sectioning) to reduce surface artefacts. (3d) Detail of a typical structure at one of the layers of the chip after final rocking polishing with Xe Plasma FIB at 3 µA. With the present workflow, large samples can be easily dealt with for sample preparation and – if needed – ready for Xe Plasma FIB postprocessing. Such long cuts can also be applied for cutting whole mobile displays, packages, MEMS, or other large microelectronic components.

[8] Here we present a 500-µm wide section of the TFT layer fine-polished with Xe Plasma FIB, however, wider sections can be prepared using this workflow thanks to the 1-mm FoV of the Xe Plasma FIB.

Memory stacked chip – long cm-sized cuts

One of the advantages of laser ablation is the high speed that can be reached for removing material that in the case of this laser can reach a sputtering yield of 3M $\mu m^3/s$ in Si. This is three orders of magnitude larger than the sputtering rate attained with Xe Plasma FIB at maximum current. Such ablation rate makes it possible to do cm-sized cuts or large mm-sized bulk-trenches in reasonable short time frames.

As an example of long-cuts capability of this laser we cut across a whole 12-mm memory chip, see Fig. 3. Apart from the long cut, the point to emphasize here is the possibility to correct for the taper angle and get a very good alignment of the cross-section plane with vertically aligned structures of the device. This is possible thanks to the tilt-capable stage allowing sample processing at tilted working angles to compensate for the natural taper angle characteristic of the laser beam (or any other Gaussian beam).
The result is deep straight walls at the cross-section or cut, Fig 3b. This is advantageous for subsequent FIB work as the straighter wall is the least FIB polishing time needs to be used, especially if the region of interest is located at depth of hundreds of microns below the surface of the device. In this particular sample, a 1-mm deep cross-section needs to be prepared in order to expose the 3 sub-memory dice (Fig. 3c) and have access to the smallest structures on each memory level, see Fig. 3d.

Flip-chip package – Deep 1mm cross-sectioning

As an additional example we present the preparation of a large bulk trench in a flip-chip on a PCB carrier. A 2-mm wide bulk trench was prepared with the laser followed by Xe Plasma FIB polishing to smoothen the cross-section wall for subsequent SEM inspection, see Fig. 4. Cross-sectioning of these type of electronic devices is a common practice that aims to make inspection of FEOL (transistor active layer) and BEOL structures (thick metal lines), and solder bumps looking for defects. Deep cross-sections also allow inspecting defects in the PCB. However, preparing such wide and cross-sections is extremely time-consuming if using Xe Plasma FIB only. Laser ablation dramatically speeds up the sample preparation time by significantly decreasing the time to prepare the bulk trench which accounts for most of the whole preparation time of these type of cross-sections. If we were to prepare a bulk stairs trench of 1 mm × 1 mm with Xe Plasma FIB only would take over 50 hours, while using laser ablation a box of 2 mm takes less than one hour. This represents a reduction of bulk-trench preparation time of 98% (based on milling rate for Xe ions and milling yield [8,9]).

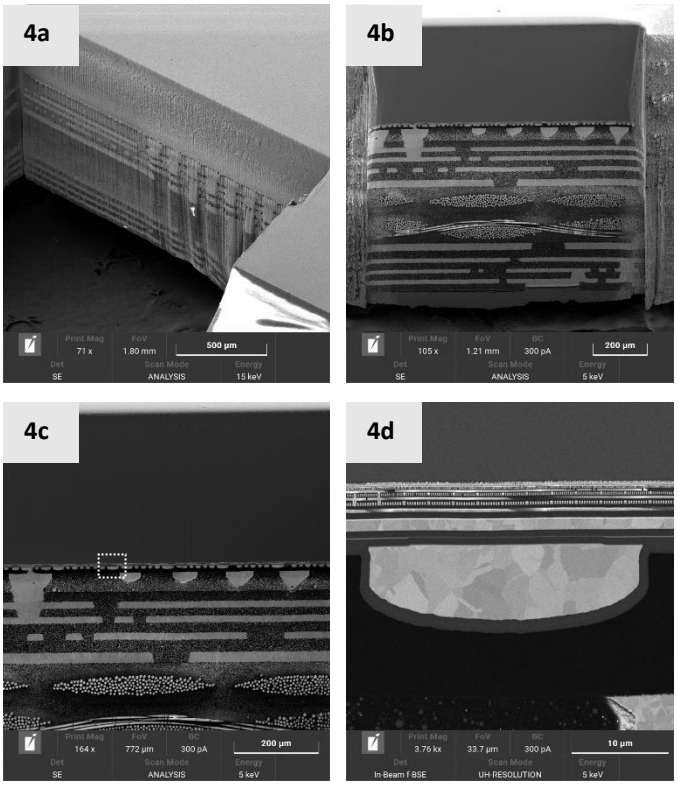

Figure 4. Cross-section on a Flip-chip package. In this additional example we show (4a) a 2-mm bulk trench prepared with the laser in 20 minutes. (4b) A 1-mm-wide section of the laser-prepared cross-section was polished with Xe Plasma FIB at initial current of 3 µA and final rocking polishing at 2 µA. (4c) Shows detailed image of the final polished cross-section where FEOL, BEOL, solder bumps, and metal layers and vias under the solder bump in the PCB are fully exposed and ready for inspection at high-resolution SEM imaging. (4d) High-resolution SEM image of the marked location on the 4c image showing more in detail FEOL, BEOL structures and a thick metal connection.

Data correlation across laser/FIB-SEM platforms

CAD-assisted navigation and endpoint detection tool

The correlation between laser and FIB-SEM (or single SEM) system is possible thanks the key compatibility that has been worked out between the SW interface of both systems – laser and FIB-SEM – with SYNOPSYS Avalon. This implementation allows GDS-assisted sample navigation on both platforms using circuit layout overlays. Once the GDS file has been calibrated with live optical camera on the laser, or SEM/FIB live image on the FIB-SEM system, an overlay image guides the user through the sample. Navigation through the sample and work is seamless and precise.

The Avalon MaskView is used to find a location or RoI on the circuit layout and with a mouse click on MaskView, the laser stage or FIB-SEM stage moves to the desired selected location. Different locations can be defined/saved/updated and loaded.

Each position can correspond to a location where a cross-section is to be prepared. Locations are bookmarked on the layout file and saved on an Avalon Data Locator file. This file can be loaded on either platform every time to navigate through the sample and quickly find with a single click a new RoI or locations that have been previously processed by either tool.

The layout overlay can be also used as an end-pointing tool. In the case of laser, the milling box for making a trench (or a cut line, etc.) can be appropriately placed according to the GDS overlay. Similarly, the polishing object used in the dedicated SW module of the FIB-SEM system, can be precisely placed according to the overlay. In the latter, the same overlay serves as a precise endpoint detection during FIB polishing; one can pause or stop the FIB process at a desired location that is guided by the reference overlay. Live SEM monitoring during FIB process can also be used in combination with layout overlay. See Fig. 5.

Bitmap overlays for data correlation and navigation to RoI

Data correlation between the laser tool and the FIB-SEM system can be implemented through bitmap image overlays. The images can be generated from other analytical instruments such as optical and infrared microscopes, micro-CT, thermal emission maps, etc. The bitmap overlay can be loaded into the SW of the laser tool and FIB-SEM system, and after a 3-point alignment the image is linked to the stage movements of either tool. Therefore, the overlay serves as a refence to precisely navigate to the desired RoI where a fault has been previously located. This makes it possible to define workflows involving both platforms to isolate the fault or defect in question, see Fig. 6.

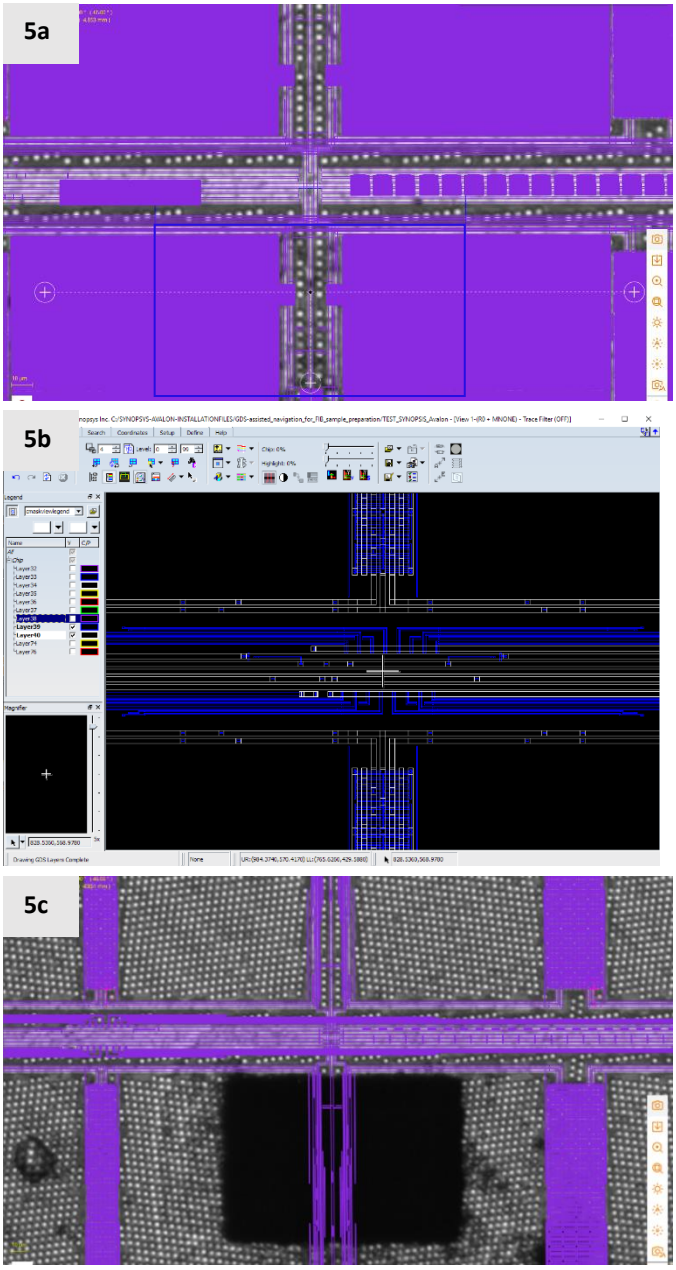

Figure 5. CAD-assisted navigation with SYNOPSYS Avalon SW for endpoint detection tool in laser and Xe Plasma FIB platforms. (5a) Optical detail camera image from the laser tool and CAD overlay of the circuit layout enabled by the integration of SYNOPSYS Avalon into laser tool SW interface. The CAD overlay guides the user to position the box milling object (blue rectangle with positioning marks) according to the desired endpoint. (5b) Avalon MaskView interface showing the circuit layout of selected layers that are used for overlay on the optical camera view. (5c) Optical detail camera image of the box after laser ablation[9] at a desired location. Some layers of the overlay were disabled to have better view of the milled box trench.

[9] For the purposes of showing Avalon integration, we prepared a small trench with laser.

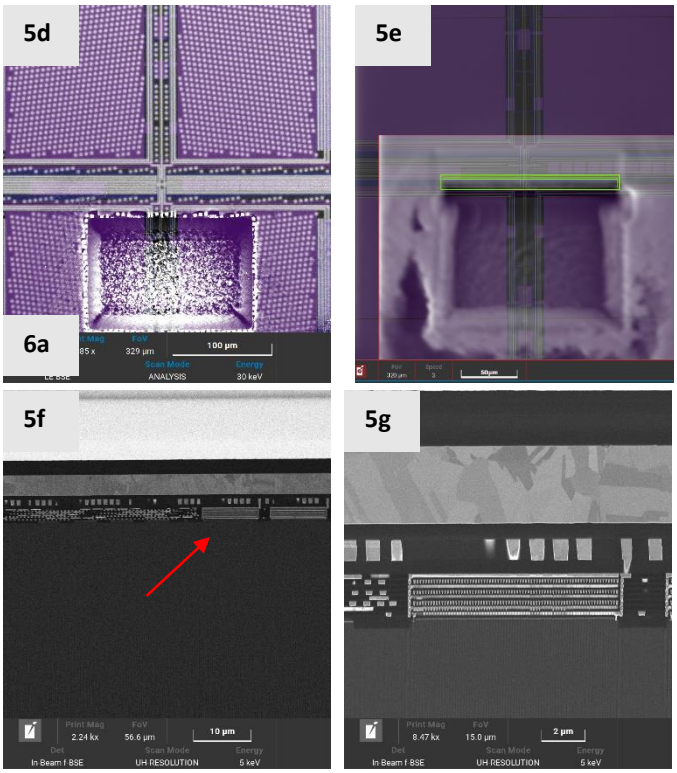

Figure 5. (5d) After laser ablation, the sample is transferred[10] to the FIB-SEM system for FIB polishing and SEM inspection[11]. Location and navigation to the previously prepared laser-trench is straightforward with a mouse click by using bookmarked locations on the circuit layout saved on an Avalon Data Locator file. SEM image at 0° with CAD overlay at the location of the laser-prepared bulk trench ready for Xe Plasma FIB polishing of the cross-section wall. (5e) FIB live image with CAD overlay during Xe Plasma FIB polishing; the circuit layout overlay is used for quick and intuitive tool for finding the RoI after transferring the sample from laser to the Xe Plasma FIB, and as a reference for endpoint. (5f) SEM image of the cross-section during Xe Plasma FIB polishing. The process is live-monitored, and the endpoint controlled by the CAD overlay. (5g) The process can be stopped or paused at a desired location or endpoint and subsequently be inspected in detail at ultra-high-resolution SEM.

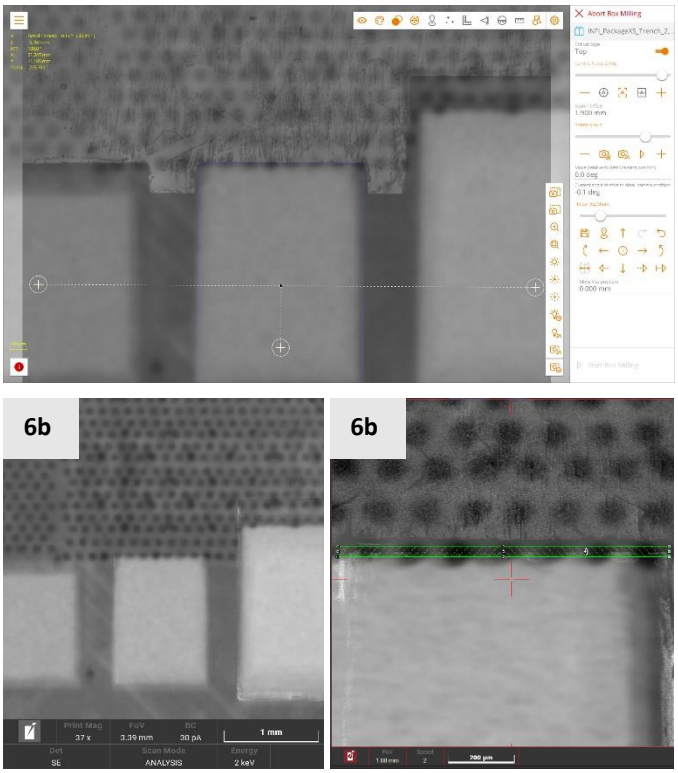

Figure 6. Bitmap image overlay for data correlation, sample navigation and end-pointing for fault isolation. (6a) View from the optical detail camera in the laser tool using an X-ray image overlay as a reference to prepare site-specific cross-sections in a flip-chip package. (6b) SEM image at 0° stage tilt with X-ray image overlay showing the cross-sections previously prepared by laser. (6c) FIB image with image overlay at 55° stage tilt ready for FIB polishing.

Summary and Conclusions

This paper presents optimized workflows for large-volume PFA of microelectronic devices. The workflows are implemented by combining a stand-alone ps-laser ablation tool with a Xe Plasma FIB-SEM system. In this synergy, the ps-laser is used to quickly remove large volumes of bulk material while Xe Plasma FIB-SEM is used – if needed – for fine surface polishing after laser processing with precise end-pointing capability to reach and stop at the feature of interest. This setting approach enables quick access to deeply buried structures thus increasing dramatically throughput in sample preparation as well as productivity since both the laser tool and the Xe Plasma FIB can run independently and continuously. A novel workflow for damage-free and delamination-free sample preparation of AMOLED displays for PFA purposes is one of the highlighted applications.

[10] A shared stage holder across platforms is the next logical development step.

[11] For the purposes of making this example clearer, we imaged the sample surface (Fig. 5d) at SEM 30 keV which made subsurface structures visible. In practice, SEM imaging at low-kV and low currents is commonly used for beam-sensitive samples. In such cases the navigation and endpoint detection during FIB-SEM work can be done using the GDS layout overlay only.

The advantage of having a tilting-capable sample stage on laser can be also applied for tapering angle correction during processing deep cross-sections. This has been explicitly demonstrated by showing a cm-sized cut on a stacked memory chip, and a flip-chip package.

Another significant feature we have also shown in this work that can help simplifying PFA workflows, is the implementation of GDS navigation dedicated SW – SYNOPSYS Avalon – on both platforms for intuitively correlating the two systems, easy sample navigation, and precise end-pointing. The use of GDS-assisted navigation simplifies finding the RoI previously processed by laser to further postprocessing with Xe Plasma FIB (or vice versa when a sample is transferred back to laser for further work). Bitmap image overlays has also been shown as a way to correlated data between the two platforms, navigate across the sample and end-pointing for fault isolation.

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