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LARGE AREA AUTOMATED DEPROCESSING OF INTEGRATED CIRCUITS: PRESENT AND FUTURE

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INTRODUCTION

Previous research has demonstrated the fundamental workflows to achieve large area automated deprocessing of integrated circuits (ICs).[1-2] This article reviews recent achievements and discusses present limitations of this type of deprocessing. It also describes future integrated circuit deprocessing tool development related to purpose-built laboratory-based hardware and synchrotron-based instrumentation. The emphasis here is on hardware, hardware configurations, and both hyperspectral and rapid image data acquisition methods. Processes related to data reduction to net list are not covered in this article.

CURRENT STATE OF LARGE AREA IC DEPROCESSING

Currently, the most efficient integrated method demonstrated to delayer a multi-layer IC device employs custom instrument automation of gas-assisted etching (GAE) with plasma focused ion beam (pFIB) delayering, sequenced with automated scanning electron microscope (SEM) montage imaging and conducted on a full die that is ultra-thinned from the backside.[1,2] This robust process has been demonstrated to automatically perform the delayering operation on multiple layers unattended and uninterrupted for a period of up to five days before being manually terminated. The process incorporates the option to acquire images at multiple voltages and with various detectors. A pair of backscatter secondary electron images acquired from a deprocessed smart card is shown in Fig. 1. Each pFIB delayering operation requires approximately seven minutes per layer, while each image montage operation takes approximately 20 minutes per layer.

A novel form of tomography was created during this process, distinguished by the fact that it involves a relatively large planar x-y area (800 × 800 μm) integrated over a relatively shallow Z depth (~3.0 μm) in 100 nm steps. An example of output from the automated deprocessing routine is shown in Fig. 2. Key elements to the success of the automated delayering process include ultra-thinning of the die from the backside prior to pFIB delayering and the ability to program the operation of the pFIB, SEM, detectors, and stage using custom Python code. Ultra-thinning from the backside to within 1-2 μm of the active layer of the die allows access to the densest features of the

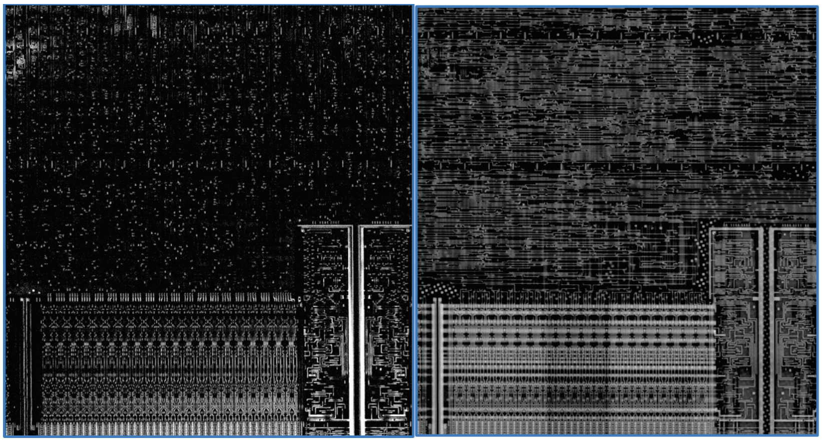

Fig. 1 **Example of image output from the auto delayering routine of a smart card. A 5-kV BSE image is shown (left) paired with a 30-kV BSE image (right). The 30-kV data peers two to three layers into the circuit, allowing forward modeling of density at depth. Data was acquired from the Florida Institute for Cybersecurity (FICS) Research, University of Florida.**

IC at the outset of the delayering process. This ensures the SEM imaging is of the highest quality with minimal surface topography at the layers, which require the highest image resolution. In addition, this workflow allows for electrical testing and interrogation of a "live" device. The fact that the ultra-thinning is also an automated, feedback-controlled precision process permits optimal integration into the overall workflow.

The ability to independently program the operation of the pFIB, SEM, detectors, and stage using Python (or any preferred language) via an open application programmer interface (API) cannot be overstated. Further, when the programmable instrument control is coupled through an independent computational engine, it creates a bidirectional communication interface to enable computationally guided microscopy (CGM). After this interface is established, it is possible to fetch images as they become available and perform near real-time data validation as well as standard operations for distortion correction, stitching, and montage display. More importantly, the bidirectional communication enables feedback to implement adaptive scanning strategies, compressed sensing, or adaptive ion dwell time at the pixel level to track and correct surface roughening. A computational engine running Dragonfly from Object Research Systems (ORS) as the image processing and 3D visualization engine was employed for this article's research. Figure 3 shows the autodelayering setup and control interface linking Dragonfly to the FIB-SEM.

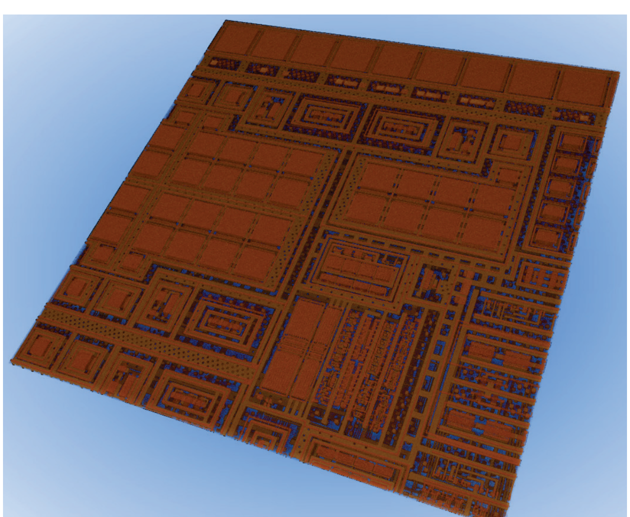

Fig. 2 **Automated plasma FIB tomography created through the automated delayering process (five layers). Integrated circuit is from a smart card chip. Data shown was generated at FICS Research. The chip was ultra-thinned from the backside prior to pFIB delayering using the Varioscale VarioMill. Tomographic data was processed using Dragonfly by ORS.**

The degree of open instrument control enabled through an API varies widely depending on the instrument vendor. However, vendors are being compelled to provide more complete and open APIs due to end-user pressure driven by opportunities in CGM. Users would be wise to negotiate the type and extent of API capabilities with vendors during an instrument purchase. While the automated deprocessing of ICs described above represents the state of the art, there are several requirements that drive the need for improvements. The main desired enhancements are related to increased data acquisition speed and larger area. The next few sections describe potential methods to increase speed and expand area coverage with laboratory-based instruments as well as synchrotron-based instruments.

THE 'IMAGING PROBLEM'

Next is an examination of the "imaging problem" and the limitations associated with traditional scanning electron imaging. It is assumed that any optimal deprocessing workflow begins with ultra-thinning from the backside of the die. For the sake of this discussion, it is also assumed

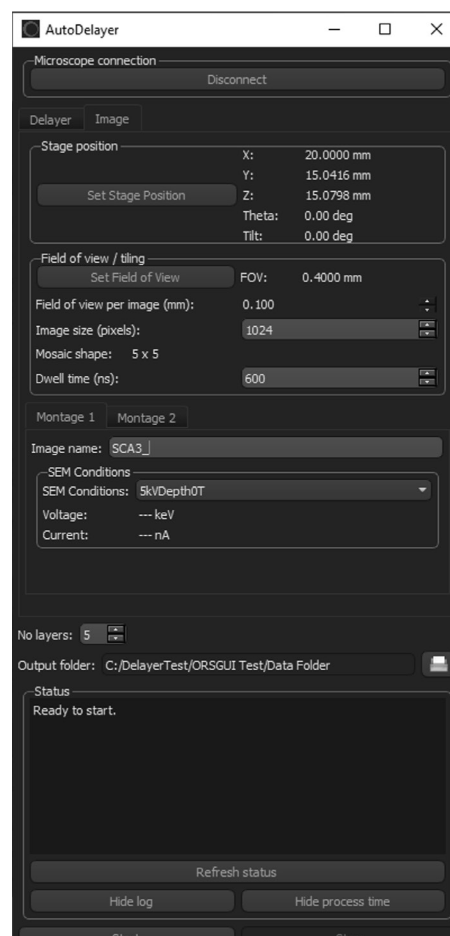

Fig. 3 **The automated delayering user interface couples communication and feedback between the computational engine and the FIB-SEM to permit CGM.**

that a total of five layers would require destructive GAE ion delayering from the backside. The imaging time represents the most significant barrier to increasing the overall speed of IC deprocessing. Consider a dwell time of 1.5 μs and individual image tiles composed of 4096 × 4096 pixels with a 100 μm^2 field of view (FOV), yielding a 24.4 nm pixel size: It would require 2.9 days to image one layer of a 1 cm^2 die. A 10 nm pixel size would require a 40 μm FOV and an imaging time per layer of 18 days, not including overhead or image overlap. Given those assumptions, total electron imaging time using a traditional SEM could require more than 90 days.

The world's fastest scanning electron microscope, a Zeiss MultiSEM, employs up to 91 simultaneous beams to drive that imaging time down to an impressive three hours. However, that technology comes at a seven-figure cost and does not integrate with a delayering process, along with other pragmatic challenges that will not be discussed here. Next is an exploration of methods used to reduce electron imaging time, other than multi-beam scanning technology, which is covered in later sections.

COMPRESSED SENSING WITH POINT SPREAD FUNCTION DECONVOLUTION

The same computational engine used to automate the delayering-imaging instrument is designed to implement other advanced CGM methods such as compressed sensing (CS) and point spread function deconvolution (PSFD). The implementation of CS in electron microscopy requires a very specific scan generator. Synchrotron Research Inc. has designed a CS scan generator for this purpose, which is coupled to CUDA programmable graphical processing units (GPUs) for CS reconstruction. Figure 4 shows a CS reconstruction and sequential blind PSFD on a synthetic sensing mask from an Intel Skylake 14 nm processor.

Denoising and image sharpening are evident, but blind deconvolution is less accurate than from a measured PSF, which is a function of an array of system conditions. In fact, a complete PSF characterization of an SEM or FIB (which can be automated) reveals the transmission function of the microscope and captures systemic and temporal deviations, therefore doubling as a health monitoring system. The application of PSFD is particularly useful in order to obtain optimal resolution at low voltage and higher currents. An automated deprocessing instrument incorporating compressed sensing could reduce imaging time by as much as fivefold, reducing the deprocessing time of five layers to approximately 18 days. This approach assumes that the upper layers would be more effectively deprocessed using methods other than destructive ion delayering and electron imaging. One such possibility, synchrotron-based tomography, will be discussed further in an upcoming issue of *EDFA.*

DEDICATED AUTOMATED IC DEPROCESSING HARDWARE

Commercial pFIB-SEM instruments are not optimized for IC deprocessing because they were never designed with such a specific purpose in mind. A typical FIB-SEM is designed to be a highly versatile platform to accommodate a wide range of applications. If an instrument configuration is designed with deprocessing of ICs as a primary objective, the geometry and functionality may be better adapted, and the software and controls better streamlined for the purpose. In addition, surface sensitive ion and electron spectrometers with small form factors have recently been developed, which add considerable analytical value at modest cost. The elemental and chemical information is extremely valuable to complete the characterization of the device, while the surface sensitivity establishes nanometer scale end point detection (EPD). The efficiency of these small spectrometers can be quite high, especially if their design is tuned to the application. Figure 5 shows an overview of a working instrument design by the authors for an advanced IC deprocessing tool currently being developed in collaboration with interested parties. Reference will be made to this platform and accompanying figures while exploring and discussing functionalities desired in a dedicated IC deprocessing

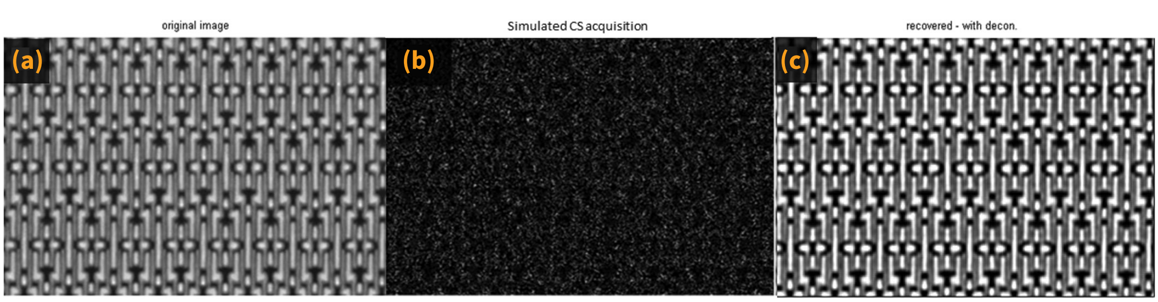

Fig. 4 **(a) Intel Skylake 14 nm processor–original image. (b) Synthetic sensing mask of (a) with 20% of the scan data. (c) Reconstructed image and PSFD applied to scan data in panel (b).**

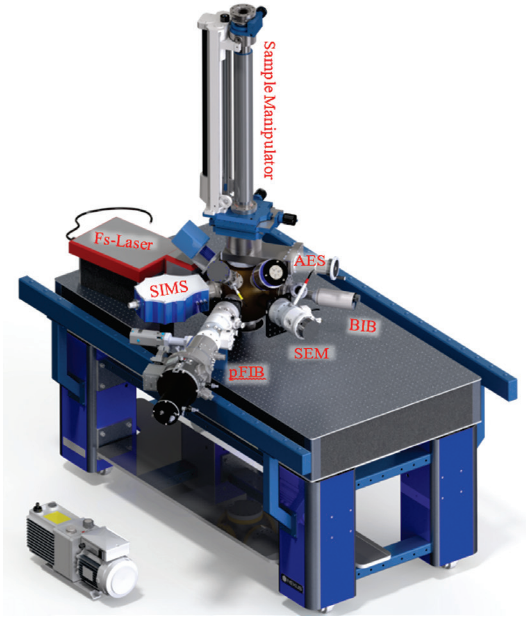

Fig. 5 **Isoview of PIE.**

instrument. The tool is configured to allow modification and probing using photons, ions, and electrons (PIE) in one instrument platform. As depicted in Fig. 6, there are various modes of processing and data collection. In Mode 1, a broad ion beam (BIB) and SEM imaging is coincident. In Mode 2, a pFIB and SEM imaging is coincident. In Mode 3, the pFIB and imaging secondary ion mass spectroscopy (SIMS) are at optimal coincidence. In Mode 4, a femtosecond laser is oriented normal to the sample surface. A "standard" gas injection system (GIS) and in-chamber electron detectors (not shown) are orientated out of the horizontal plane. The compact Auger electron spectroscopy (AES) detector is also located out of the horizontal plane and may be operated concurrently with the SEM column. The configuration is based on actual available hardware components with accurate form factors. Note that the primary probes are arranged in the horizontal plane, with various detectors and accessories above the horizontal plane with a vertical sample handling arrangement. Several elements of the hardware and instrument controls are based on prior experience with components used in synchrotron-based instrumentation. The platform is intended to be ultra-high vacuum compatible, but may also operate in the vacuum range typical for commercial electron and ion microscope platforms. The automated sample handling can accommodate several backside-loaded die along the vertical length of the sample carrier frame channel. A previously proven transfer design is used to capture the backloaded die into platens, which then insert into the vertical sample manipulator channel. The manipulator allows precision x-y-z-r motion. The sample may be rotated to face normal to any probe and the x-y translation can be used to control working distance with respect to any probe or set of probes. This vertical sample carrier channel was originally conceived to permit routing for cryogenic cooling of biological samples dispersed onto a silicon wafer. The overreaching concept of the platform addressed is to combine a BIB and FIB into a common workflow to permit a range of resolution and scale to the physical delayering process. Rapid improvements in the affordability, reliability, and reduced form factor of femtosecond laser sources make them a very attractive addition to the workstation. The augmentation of a new generation of compact ion and electron spectrometers add yet another new dimension of elemental and chemical analysis to the data cube, while acquiring signals currently being ignored during the process. The sample handling is designed to easily accommodate multiple die for extended runs with a simple, reliable, and programmable range of motion. These represent some of the attractive features and functions of a dedicated IC deprocessing instrument.

The instrument control platform for the proposed dedicated IC deprocessing instrument is based on the Experimental Physics Industrial Control System (EPICS) (https://en.wikipedia.org/wiki/EPICS). EPICS is an open

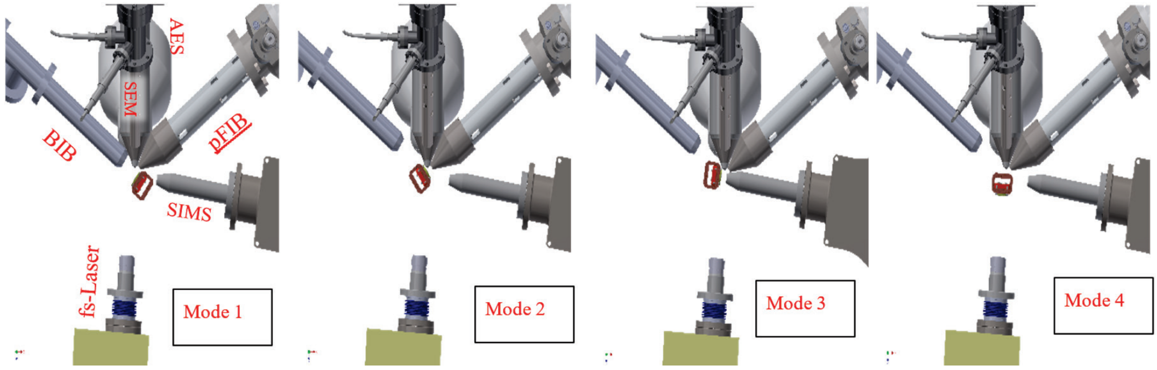

Fig. 6 **PIE platform depicting primary deprocessing and analysis modes. Mode 1: Configuration for BIB milling and SEM imaging. Mode 2: Configuration for pFIB delayering and SEM imaging. Mode 3: Configuration optimal for pFIB-SIMS imaging. Mode 4: Configuration for nonthermal bulk ablation.**

source set of network-based software tools and applications, which provide a software infrastructure for use in building distributed control systems commonly used around the world in synchrotron facilities and particle accelerators. Using an EPICS backbone allows integration of well-established methods while creating a uniform standard for instrument control that may be openly developed.

GAS ASSISTED ETCHING

Regardless of the ion source, an effective gas chemistry is critical to enable ion-based delayering, and gas chemistries are available for pFIB-SEM delayering. In general, the goal of the gas chemistry in conjunction with appropriate ion beam energy and current density is to homogenize the material removal of very heterogeneous structures consisting of varying metal density (i.e., copper and tungsten) and interlayer dielectric comprised of porous silicon. To achieve this, the gas chemistry is designed to impede the rate of the faster milling components in order to balance the process. Gas chemistry may be modulated depending on the metal density in the region of interest. In the specific case of gallium FIB delayering, the gas chemistry also plays the critical role of minimizing redeposition by volatilizing sputtered species. Indeed, while gallium may be used effectively for delayering with an appropriate delayering gas, the fact that gallium is not inert makes it a less desirable source. Without a suitable gas chemistry, the interaction between redeposited gallium and copper can be extremely problematic. This issue is demonstrated in Fig. 7, which shows the "pooling" of gallium-copper interphases surrounding the etch area. Moreover, when considering very large area deprocessing on the scale of an entire die, it is important to ensure the surface does not become gas-starved. A single standard GIS needle proximal within ~150 μm of the surface will not evenly distribute an etch gas across an entire die, therefore alternatives must be sought. An alternative could take the form of multiple GIS needles directed onto the die, incorporation of a gas-concentrator shield, or even allowing the entire chamber environment to back-fill with the desired gas chemistry. All such options have specific advantages and disadvantages. Ideally, the best scenario provides an option for multiple gas chemistries and the ability to regulate specific ratios of chemical species depending on the metal composition and density. In the working design, the alternative of embedding the plumbing for the gas chemistries into the sample carrier frame is considered. The gas chemistries can be manifolded and dispersed within the frames surrounding the four sides of the slightly recessed back-loaded die. This is another approach to achieving sufficiently uniform and concentrated gas chemistry at the near surface of the full die.

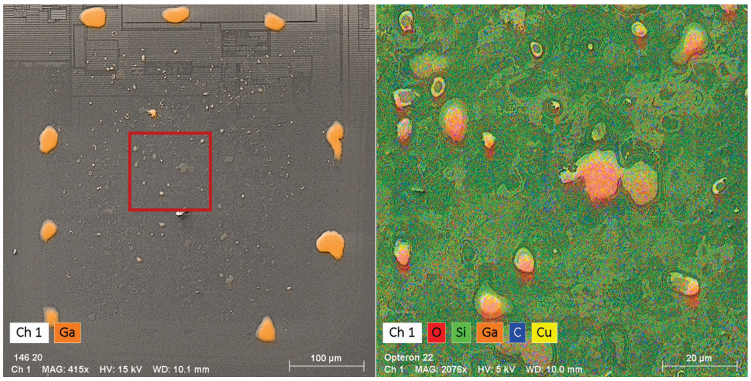

Fig. 7 **Interaction of Ga and Cu without gas-assisted etch chemistry. Left panel shows Ga EDS map is overlaid onto the SEM image, enclosing the region where the gallium FIB was etched in a 400 μm^2 area from the backside on an Opteron die. Right is a higher magnification composite SEM-EDS image taken from the area outlined in the left panel red box. Data shown was collected at FICS Research using a Bruker EDS.**

ION SOURCE ALTERNATIVES

A pFIB is not technically required to perform automated IC deprocessing. However, it does provide a superior method to precisely open well-defined areas on the micron scale. Other source gases are also possible in a pFIB, such as argon, oxygen, nitrogen, helium, and sulfur hexafluoride. While these alternative gases have an inferior milling rate compared to Xe, they provide varying aspect ratios, or in the case of species like O and SF_6, deliver active chemistry for secondary ion yield enhancement or chemical etching. Therefore, the pFIB is a powerful component of a comprehensive deprocessing tool. But in many ways, a BIB source is more efficient over large areas and more economical in terms of capital expense to address the generic delayering of a full die. A BIB can effectively cover an entire die with variable spot size and scanning options. It can also be configured for Xe, Ar, and other gases. While a BIB has lower brightness than a pFIB, that is not the most critical parameter when considering large area deprocessing. The SEM in this platform concept is located between the BIB and pFIB so that imaging may be performed when using either ion source.

COMPACT SIMS INSTRUMENTATION

A pFIB is a required ion source when ion delayering is conducted in combination with imaging SIMS, which allows simultaneous collection of secondary ions generated during the GAE ion delayering process. While most of the sputtered material is in the form of neutrals, the yielded ions may be captured and analyzed to add elemental surface composition. If post-ionization methods are applied (i.e., laser post-ionization), the yield is further enhanced. SIMS hyperspectral data may in turn be combined and interleaved with SEM imaging data using data fusion methods. As a surface analytical technique, the SIMS functions as a sensitive EPD scheme to monitor delayering progress and uniformity. The compact SIMS shown in Fig. 8a is the design of Ion Innovations and utilizes a novel miniaturized adaptation of a classic magnetic sector mass spectrograph. This mass spectrograph incorporates compressive sensing techniques (spatially coded apertures) and stigmatic lens designs to maintain high resolving power and sensitivity for its size.[3-4] Dual polarity (not simultaneous) and single polarity designs are available and offer simultaneous acquisition of the full mass spectra within a specified range.[5]

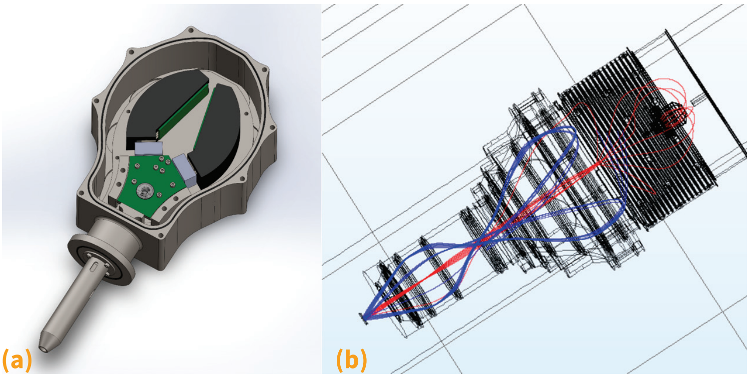

Fig. 8 **(a) Compact SIMS instrument designed by Ion Innovations for elemental mapping and end point detection during the delayering process. (b) Compact AES in development by PanoScientific LLC, showing selected electron trajectories. Overall length is 300 mm.**

COMPACT AES INSTRUMENTATION

Analogous to the benefits of SIMS while conducting GAE ion delaying, AES contributes complementary analytical information concurrent with SEM image data acquisition. In addition to the type I, II, and III secondary and backscatter electrons being induced, Auger electrons are also being induced by the primary electron beam with a yield inversely proportional to the x-ray yield. Thus, AES is very attractive for light elements, including lithium. AES provides not only elemental information, but also chemical signatures for many compounds used in ICs, such as nitrides and silicides. In addition, the surface sensitivity means that AES is also good for EPD. Similar to the SIMS hyperspectral data, AES hyperspectral data may also be integrated using data fusion methods. The compact AES detector envelope shown in Fig. 8(b) is a prototype development of PanoScientific LLC and may also be operated in an x-ray photoelectron spectroscopy mode.

FEMTOSECOND LASER

The femtosecond laser shown in the hardware model serves a dual purpose: It may be applied for nonthermal ablation directly, or for post-ionization during the SIMS data collection. There is also the potential for laser-mediated chemical etching. Together, the extremely short pulse laser and variable pulse laser are a powerful component of any deprocessing tool.

CONCLUSIONS

An API with a custom graphical user interface has been applied to link a computational engine for instrument control, data collection, and data visualization with bidirectional communication to a pFIB-SEM platform to achieve automated and unattended IC deprocessing (delayering) on a full die ultra-thinned from the backside. This instrument control link forms the basis for the much broader and more general methods of CGM. Such a platform facilitates the rapid development of functionality outside the resource limits and priorities of original equipment instrument vendors.

This article describes advances for future laboratory-based instrumentation dedicated to IC deprocessing using a CGM platform. Applications include CS and PSFD modules with machine learning to enhance data collection speed and resolution. A “PIE” instrument configuration for IC deprocessing is proposed, which incorporates several processing modalities and analytical data collection modes beyond what is currently employed.

A future article will highlight the application of synchrotron chemical imaging and x-ray tomographic methods to integrate with the deprocessing workflow. This workflow would blend electron-based imaging from the backside with synchrotron-based x-ray tomographic methods to complete the reconstruction.

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Edward L. Principe obtained a Ph.D. in engineering science from The Pennsylvania State University and M.S. and B.S. degrees in mechanical engineering from the University of Central Florida. He is founder and president of Synchrotron Research Inc., a designer and manufacturer of imaging NEXAFS tools. Principe has authored two textbook chapters on FIB-Auger and FIB-based 3D nanotomographic reconstruction and co-authored the EDFAS Best Paper in 2013 and EDFAS Outstanding Paper in 2017. He holds two patents in FIB-based 3D reconstruction and is focused on the development of computational guided microscopy.

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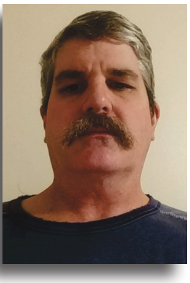

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