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Latest advances in automated TEM metrology and failure analysis of semiconductor structures

Thermo Scientific™ Metrios™ Smart Automation streamlines TEM metrology and failure analysis by automating complex workflows, reducing the burden of manual operations and enhancing data quality and scalability.

Why are automated TEM metrology semiconductor workflows needed?

Development of advanced semiconductor device architectures like gate-all-around (GAA) transistors and 3D memory devices has created a significant challenge in fabrication process control and failure analysis, increasing the demand for high-quality scanning transmission electron microscopy (S/TEM) metrology data. Further, the demand for consistency and repeatability of data from an increasing volume of TEM samples, coupled with a shortage of skilled labor, has made fully automated S/TEM metrology workflows a necessity for the industry, as they reduce operator-dependent variability and help minimize human bias and error. The introduction of recipe-based S/TEM automation about a decade ago, via Recipe Editor in the Thermo Scientific Metrios Scanning Transmission Electron Microscope S/TEM, marked a significant step toward fully automated S/TEM metrology workflows and has since emerged as a standard for high-volume, high-precision TEM analysis in the semiconductor industry.

Now, a decade later, Smart Automation introduces a more autonomous and intelligent approach to S/TEM automation, leveraging machine learning and computer vision to further advance consistency, reduce manual effort, and address scalability challenges in today's semiconductor manufacturing environments.

How does Metrios Smart Automation enhance TEM metrology?

Recent advancements in TEM hardware and software have enhanced the S/TEM process automation workflow, significantly reducing or eliminating the need for manual intervention and increasing the consistency and repeatability of results. For example, the Smart Stage in the Metrios 6 (S)TEM automatically inserts and retracts the sample holder into and out of the microscope column, eliminating not only manual handling but also reducing the potential for human errors or inconsistencies. Our latest automated TEM metrology software package, Metrios Smart Automation, offers a fully automated imaging workflow supporting a wide range of sample types such as cross-sections of advanced logic and memory devices (GAA, DRAM), plan-view devices (3D NAND), and cross-sections of blanket film samples. Metrios Smart Automation utilizes machine learning and computer vision methods to substantially reduce automation set-up time and provide substantial improvement in ease-of-use and scalability with improved robustness and throughput. Within the workflow, critical microscope alignments are automated and maintained to help ensure high-quality and robust S/TEM automation. Metrios Smart Automation represents a notable step forward in the evolution of semiconductor metrology, addressing the need for efficient, reliable, and repeatable automated solutions.

What is the framework of Smart Automation?

Metrios Smart Automation is a software application designed to automate S/TEM metrology workflows[1]. It provides high precision and scalable automated acquisition of TEM, STEM, and Energy-dispersive X-ray spectroscopy (EDS) data for yield enhancement and failure analysis. Metrios Smart Automation introduces a recipe-free approach that significantly accelerates the time-to-recipe workflow compared to traditional methods. While building upon the pioneering automation capabilities initially introduced by the Metrios Recipe Editor—an innovative solution—Metrios Smart Automation further enhances ease of use and flexibility, reinforcing the Metrios (S)TEM's notable position in automated TEM solutions. The introduction of machine learning and computer vision methods are the

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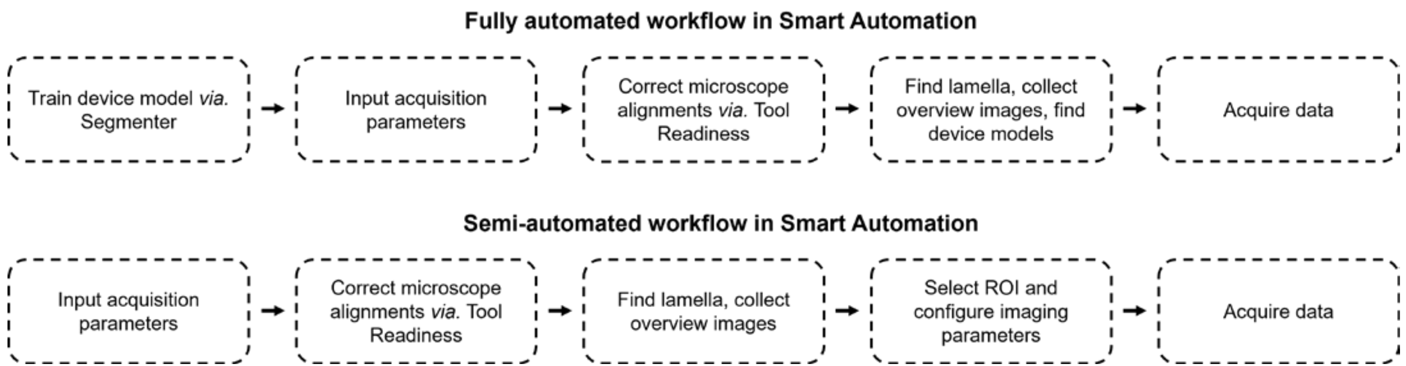

Figure 1. Steps involved in automation workflows within Smart Automation.

distinguishing features of Metrios Smart Automation. This targeted application of advanced machine learning tools allows for rapid detection and navigation of TEM lamella and features within, and for collection of high-quality, high-resolution metrology data.

Metrios Smart Automation currently supports fully automated workflows for cross-section front-end devices like logic and memory devices, plan-view devices, and cross-section blanket film samples, all without user intervention *(Figure 1)*. The fully automated workflow relies on user-trained device models to acquire high-resolution metrology data. These models are generated by users through our web-based software interface, Segmenter. Additionally, a semi-automated workflow is available for logic and memory devices, offering flexibility by generating a large overview image of the features, allowing you to select and draw a region of interest (ROI) for data acquisition, without the need for a user-trained model.

How to train models in Smart Automation

Segmenter

Segmenter is a web-based software interface that allows you to interact with the Metrios machine learning server to train and generate device models. Initially, you can manually annotate

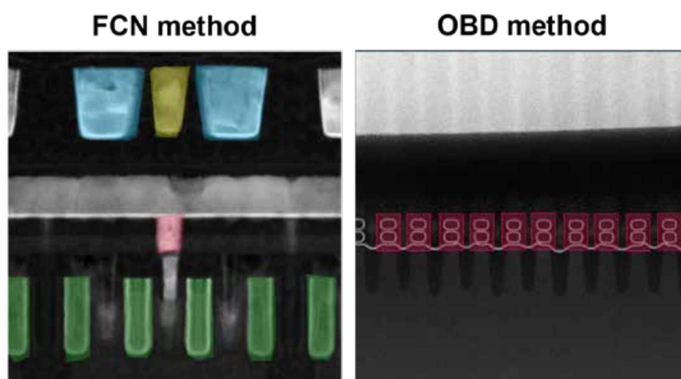

Figure 2. Illustration of device annotations of SRAM device by FCN method that involves drawing polygons around the feature of interest and GAA-nanowire device by OBD method that involves drawing bounding boxes around the feature of interest.

multiple devices by selecting and labeling features within an image *(Figure 2)*. Subsequently, the machine learning server builds a neural network model, based on these annotations, which will be used to detect and navigate to the desired features during the automated workflow.

Currently, you have the option to train device models using two types of neural networks *(Figure 2)*:

1. A semantic segmentation method based on the fully convolutional network (FCN) architecture.
2. An object detection (OBD) method.

The FCN method involves annotations with keypoints and polygon masks around the features of interest, providing a detailed, pixel-wise classification of the entire image. Although this method requires longer training times, it is more robust with fewer training images and can handle greater variation in the features of interest. The OBD method uses bounding boxes for feature annotation, enabling faster annotation and quicker training. This method identifies and localizes individual objects within an image, allowing for precise object location. For features with minimal variation, the OBD method is optimal, requiring less training time.

Once the model is trained, you can initiate automated image acquisition with Metrios Smart Automation. First, you need to input acquisition parameters such as sample type, imaging mode (STEM, TEM), device model, and other acquisition parameters such as magnification (or field of view), exposure time (or dwell time), binning, number of images, and so on.

Ensuring automation robustness and flexible workflows

Tool Readiness

To minimize the need for human interaction while ensuring high-quality data and robust automation performance, we have integrated Tool Readiness, an automated alignment service within Metrios Smart Automation. This feature continuously

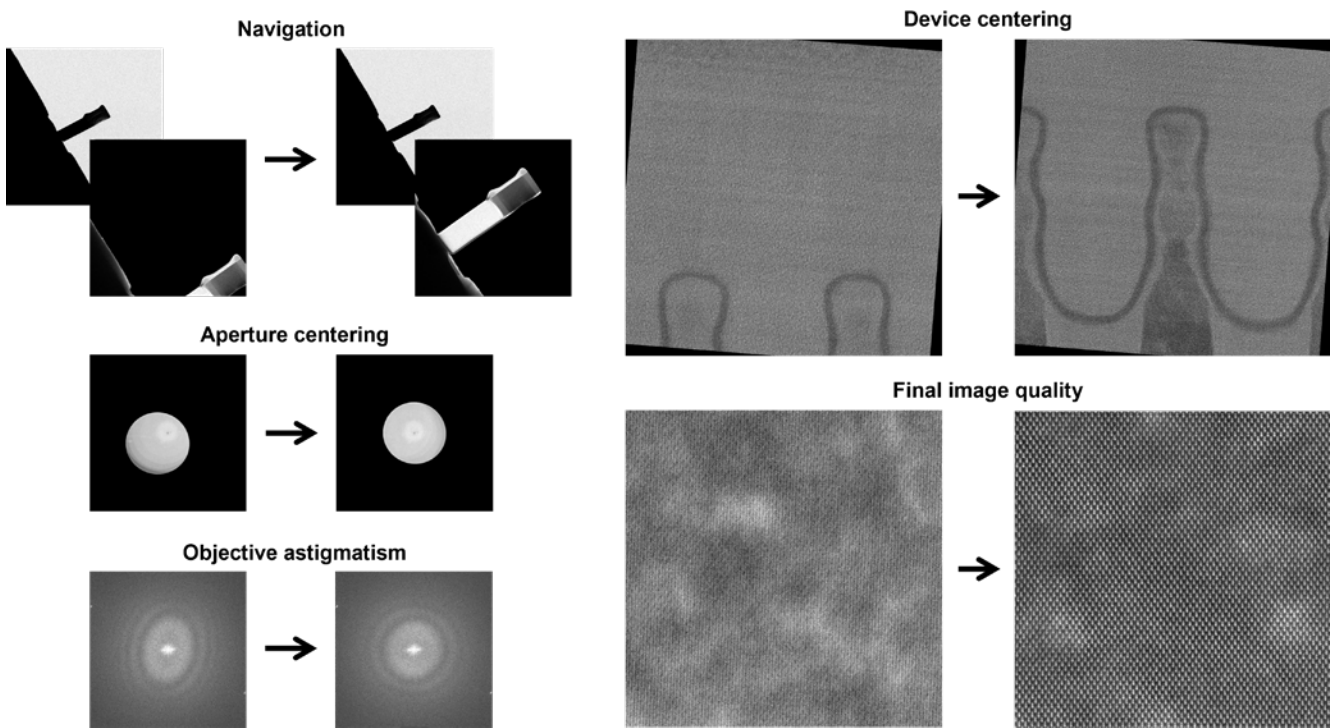

Figure 3. Illustration of various alignments corrected by Tool Readiness for robust S/TEM process automation.

monitors alignment stability, automatically corrects deviations, and maintains optimal alignments within predefined acceptance criteria *(Figure 3)*. The results and history of Tool Readiness runs are stored and displayed in the Tool Readiness Dashboard, which provides a comprehensive overview of all the alignments such as expiration time, results, and configuration settings.

Automated workflows in Smart Automation

Fully automated workflow

Once the validity of the alignments is confirmed, the automated workflow begins by detecting and navigating to the lamella *(Figure 4)*. Upon locating the lamella, the machine-learning-enabled Smart Align Zone Axis algorithm orients the silicon

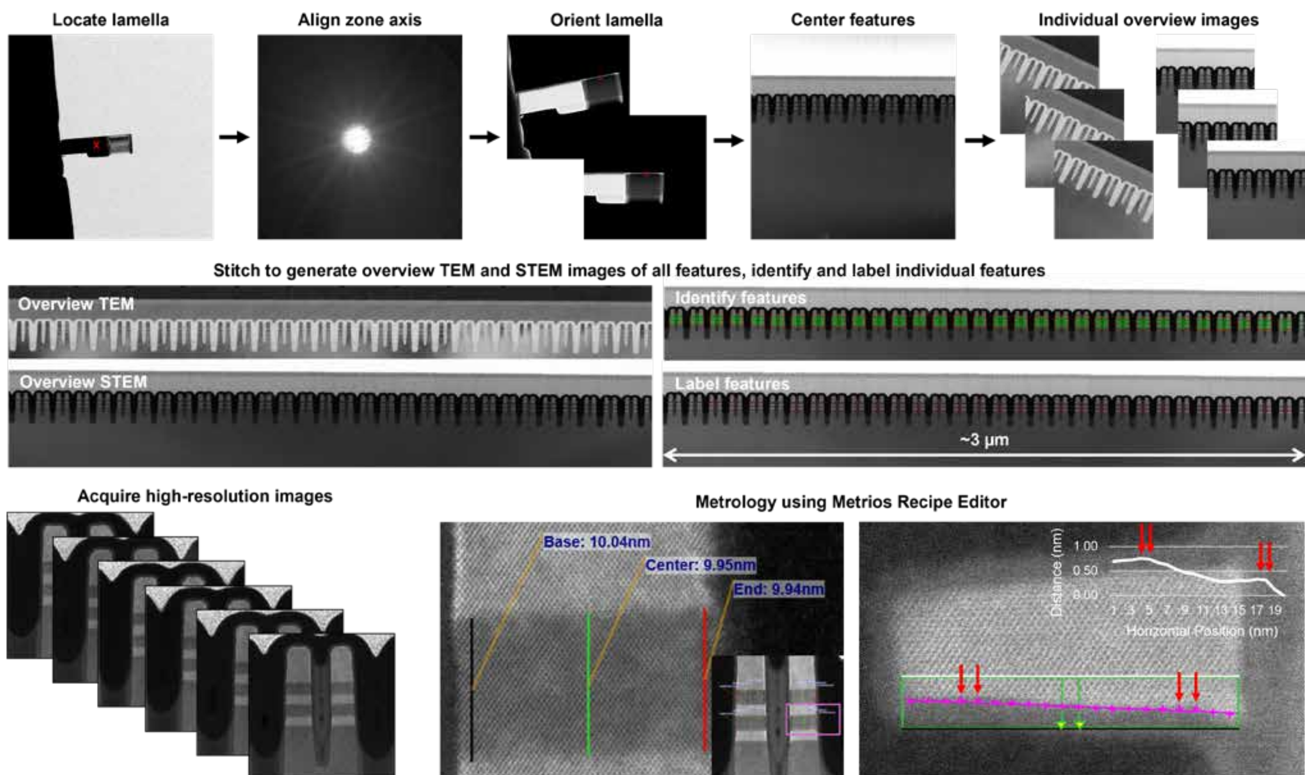

Figure 4. Fully automated workflow of cross-section of gate-all-around (GAA) structure. The snapshots illustrate the process from lamella detection to the acquisition of high-resolution GAA device images performed by Metrios Smart Automation. Automated metrology performed on these high-resolution images via Metrios Recipe Editor illustrates the critical dimensions of Si layer at three positions (base, center, and end), and a line fit reveals sub-1 nm variations (red arrows) at the bottom of the Si nanosheet.

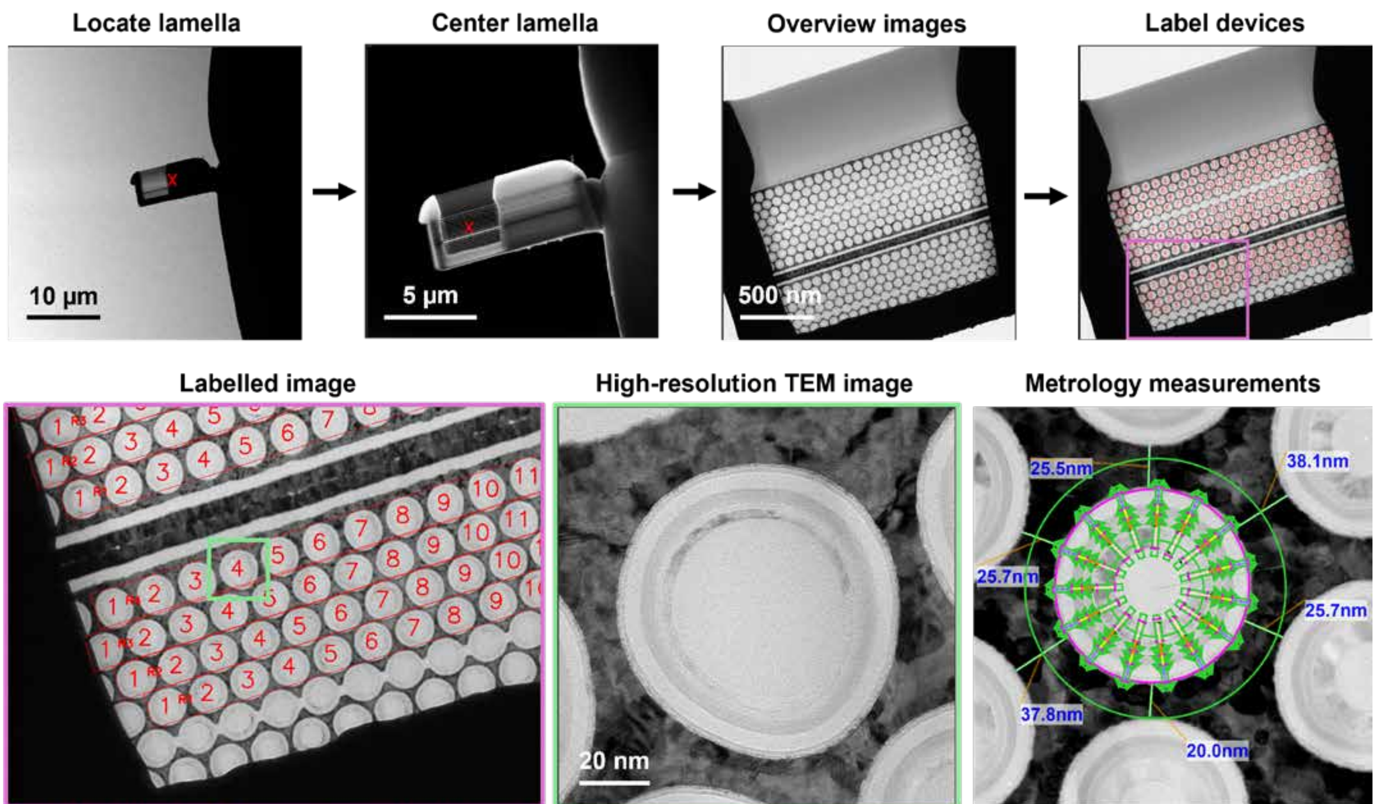

Figure 5. Automated TEM workflow of planar 3D NAND in Metrios Smart Automation. The snapshots demonstrate detection, centering, labelling, and TEM acquisition of plan-view 3D NAND devices. Automated metrology of plan-view 3D NAND using Metrios Recipe Editor.

substrate to any specified industry-standard crystal orientation, such as [100] or [110]. Subsequently, a large-scale overview of the features is acquired. Based on the user-trained model, individual devices are uniquely identified and high-resolution S/TEM images, EDS maps, and EDS line profiles are acquired. The collected data can then be used for metrology measurements via the Metrios Recipe Editor[2].

The fully automated workflow in Metrios Smart Automation also supports the automated TEM acquisition of plan view devices such as 3D NAND devices *(Figure 5)*. Here, the lamella is located and centered based on the factory-supplied machine learning models, followed by acquisition of an overview image of the thin window. Then, a machine learning algorithm locates individual 3D NAND cells, and high-resolution TEM data is acquired. Critical dimensions of 3D NAND can then be measured using the Metrios Recipe Editor.

Metrios Smart Automation also supports automated imaging of blanket film cross-sections[3], despite the challenges posed by the lack of inherent features such as un-patterned GAA nanowire samples *(Figure 6).* A simple fiducial (a pit etched into the sample during lamella preparation in the FIB) is necessary for machine-learning-based navigation and targeted acquisition. Similar to logic device automation, the blanket film workflow identifies and aligns the lamella to the zone axis. Subsequently, a user-trained model identifies the fiducial, and edge finders detect the silicon interface. Finally, high-resolution data of blanket film layers are acquired in a region of interest away from the fiducial and free from beam exposure.

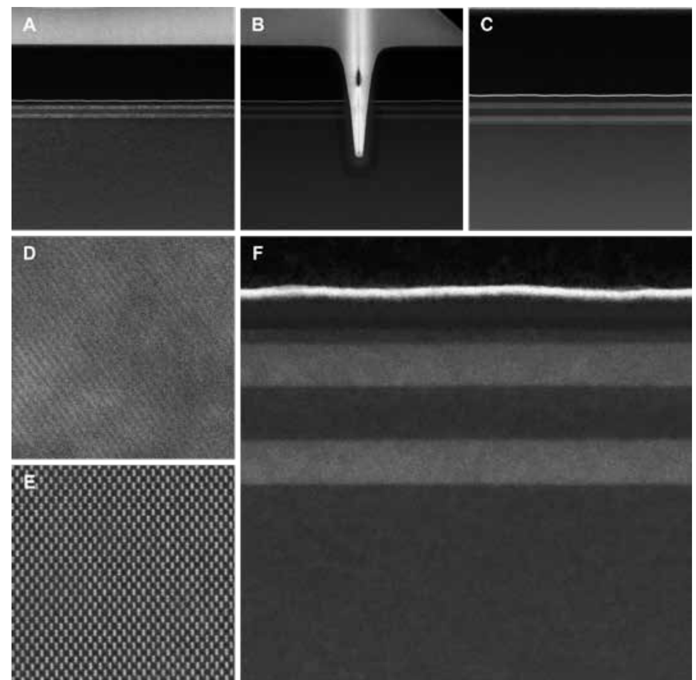

Figure 6. Automated workflow of blanket film cross-section. A) Un-patterned deposition of GAA-nanowire layers. B) Notch fiducial etched and filled with tungsten using a Thermo Scientific Focused Ion Beam Scanning Electron Microscope (FIB-SEM). C) Metrios Smart Automation identifies the silicon interface (green line) in the blanket film. D) Lattice image before correction. E) Lattice image after correction. F) High-resolution STEM of blanket film cross-section.

Metrios Smart Automation is designed to efficiently collect a series of images based on repeating patterns or groups of individual devices as determined by user-trained machine learning models. By utilizing a visual instruction set, you can run fully automated workflows to acquire multiple repeating

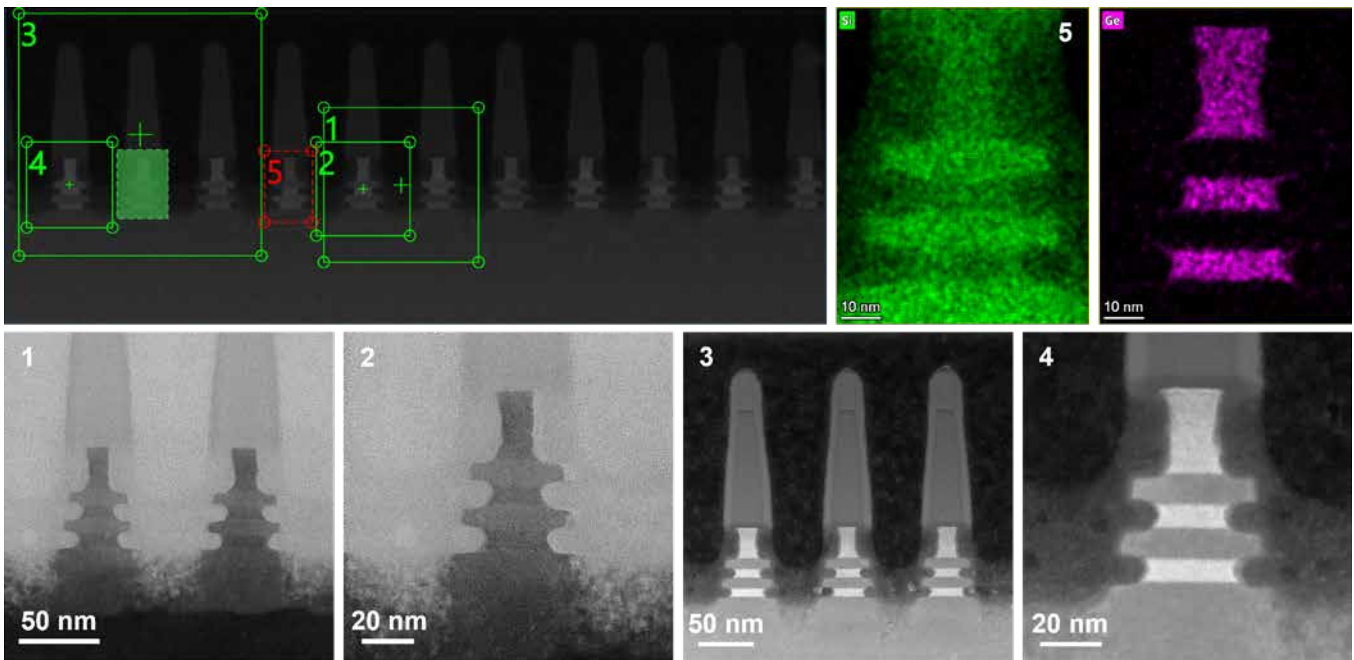

Figure 7. Visual instruction set-based automated workflow of cross-section of gate-view GAA forksheet. Snapshot of visual instruction set template image. The highlighted green box represents the selected reference model. The green (TEM and STEM) and red (EDS map) boxes represent the imaging positions selected relative to the reference model. High-resolution TEM, STEM, and EDS map reveals the quality of the forksheet structure such as height, curvature, local variations in dimension, topology, and composition.

features of complex models with precise control over the acquisition types *(Figure 7)*. The visual instruction set uses a template of feature positions identified by the machine learning model for data acquisition. Initially, you create this template on an image using the existing model, selecting reference points on the model. Regions can then be added relative to the reference points, and imaging modes and parameters can be adjusted as needed. This template can be used immediately in the Metrios Smart Automation workflow or saved for future use. This process allows for the rapid creation of a complex instruction set. The visual instruction set enables automated imaging of grouped features using various imaging modes (such as TEM, STEM, EDS line profile, and EDS maps), providing greater control and specificity over the acquisition regions.

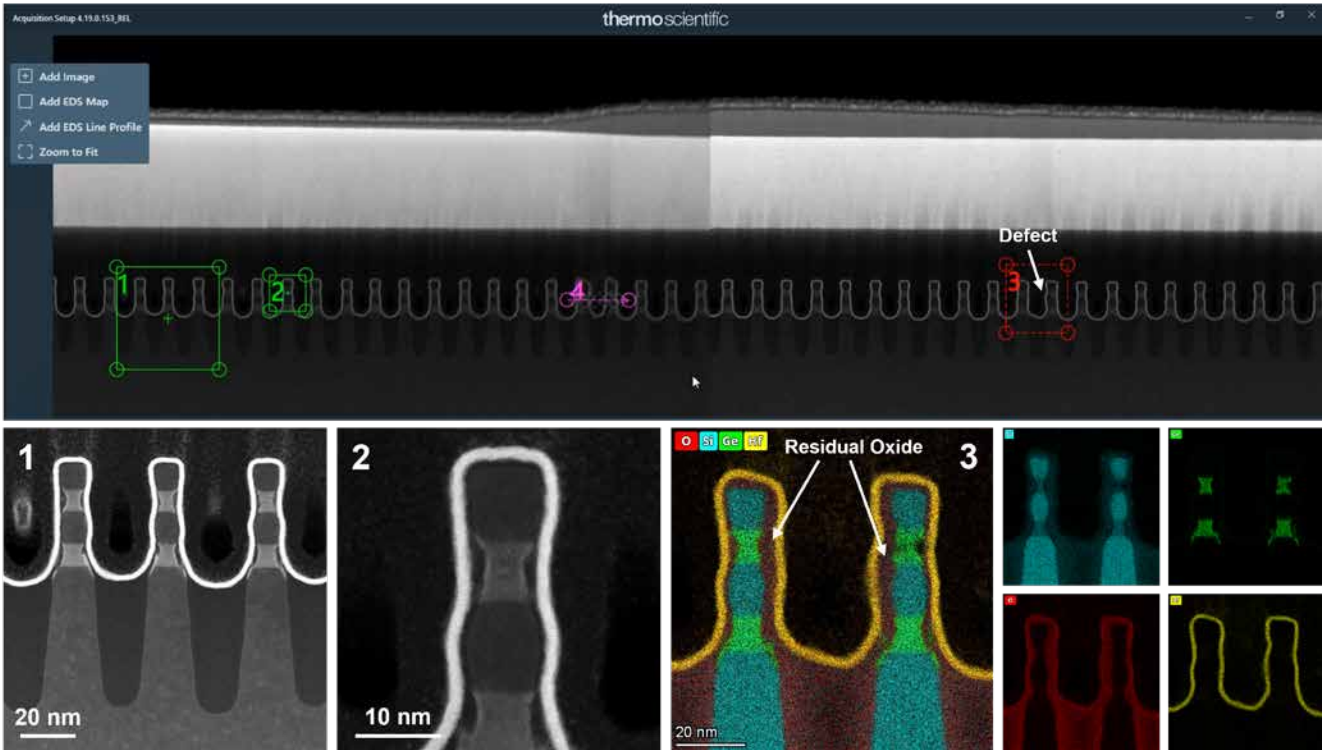

Figure 8. Semi-automated workflow of fin-view GAA-nanowire cross-section demonstrates the selection of regions of interest (ROI) and the acquisition of STEM and EDS maps. The defect region is specifically chosen for EDS acquisition, permitting failure analysis and detection of a residual oxide layer in the vertical walls of the fins, while high-resolution STEM is simultaneously acquired from other intact devices for metrology characterization.

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Semi-automated workflow

Metrios Smart Automation enhances flexibility by enabling process automation without requiring user-trained models. In the semi-automated workflow, after capturing a series of overview images, a popup window displays the stitched large-scale overview image, allowing you to manually select regions of interest for high-resolution data acquisition by drawing bounding boxes around the desired areas *(Figure 8)*. You can then set acquisition parameters such as magnification (or field of view), defocus, and exposure time (or dwell time). Once the region is defined, the automation workflow acquires images and EDS data based on these settings. This approach provides flexibility and control over which regions are imaged, allowing for tailored data collection based on specific needs, such as failure analysis. For example, you can collect images at different magnifications, including EDS line profiles and maps, within the same acquisition setup *(Figure 8)*

Summary

Metrios Smart Automation is an advanced software application designed to automate TEM metrology workflows for semiconductor fabrication process control and failure analysis.

Leveraging advanced machine learning and computer vision techniques, Metrios Smart Automation has been developed to cover a wide array of sample types such as advanced logic devices, DRAM, SRAM, plan-view 3D NAND, blanket film, and more. The recipe-free nature of Metrios Smart Automation is highly intuitive, easy to learn, and user-friendly, offering an improved user experience and substantially reducing the time-to-recipe.

Furthermore, Metrios Smart Automation offers flexible data acquisition options to meet diverse customer needs. For fully automated image acquisition, user-trained machine learning models are deployed, enabling precise targeting and consistent imaging without manual intervention. Alternatively, Metrios Smart Automation can operate in semi-automated mode without the need for user-trained models. This mode allows you to manually select regions of interest for data acquisition, which is ideal for low-volume sample types. Metrios Smart Automation is a versatile software package that advances automated TEM metrology. It delivers precise and consistent metrology solutions, establishing new standards for semiconductor fabrication process control and failure analysis.

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