Artificial Intelligence for SEM Imaging and Metrology

András .E. Vladár
National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899
andras@nist.gov

Artificial intelligence (AI) technology is at its beginnings, and it may not be sufficiently functional (see Fig. 1) for immediate widescale implementation for SEM-based wafer and mask critical dimension (CD), overlay, and defect metrology of nanometer-scale structures used in integrated circuit (IC) production. Nonetheless, one can already see that all segments of SEM imaging and measurements will benefit from it, and it likely will stimulate the development of new, much more capable, albeit more complex, SEMs and measurement methods. AI will help put physics to work in designing SEM-based measurements by identifying the best-suited instrument parameters and analyzing acquired data through rigorous Monte Carlo simulation and fast analog computational methods.

SEMs can deliver reliable information about the size, shape, composition, and location of sample structures of interest, which is especially important for IC technology development and control. The high speed of generating results is paramount for throughput and cost of ownership reasons and to minimize the alteration of the sample and the detrimental effects of the nm-scale unwanted motions of the sample and the electron beam. Without AI, carrying out these complex and complicated tasks in entirely optimized ways is impossible, which is necessary because nm-scale structures or their sub-nm variations comprise only a few dozen atoms, so their signals are inherently weak and noisy. The main segments of SEM-based dimensional metrology that will benefit from AI are: information, i.e., measurement data acquisition, separation or amplification of the needed information from unnecessary ones (through, e.g., denoising), analysis of measurement data to extract the information required for the decisions or identification of problems in IC production process, and for finding correlations and relationships in the vast data that can help the production yield.

Information, measurement data acquisition: AI can help in the design and implementation of on-the-fly, measurand-optimized sparse scanning of the primary electron beam over the area of interest within the field of view and when detected, for every pixel within it, all based on the required uncertainty of the measurand while minimizing acquisition time. The point is not to acquire information one doesn't care about or already knows sufficiently. The complete optimization will likely require laser interferometry for sample navigation and, after arriving at the area of interest, for passive or active predictive drift compensation and acquisition. The tiny structures of future ICs will require fast, sub-1 nm accuracy primary electron beam positioning in the primary electron beam scanning system.

Separation or amplification of the needed information from unnecessary ones: SEM images contain several types of instrument- sample- and environment-specific noises. For most of these robust denoising solutions exist already, but a comprehensive AI solution must be implemented with on-the-fly denoising coupled with sparse image/data acquisition. The optimal solution is complex; it depends on many parameters and changes as the information sought is acquired, but it is only possible with AI. AI-based real-time denoising and sparse acquisition can speed up measurements significantly; see an example in Figure 1. Finding the area or objects of interest within the noisy image of a field of view, then moving the primary electron beam to the image pixels where the sought information is located, and acquiring it for the time needed to achieve the required uncertainty can only be accomplished with AI controlling the process.

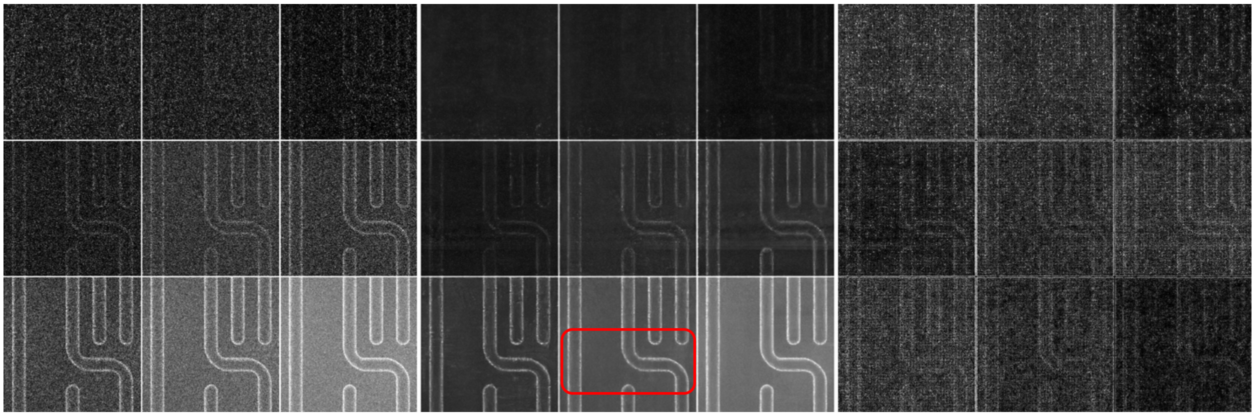

Figure 1. Various noise and contrast levels in simulated SEM images of IC lines. The original images are on the left, their AI-denoised versions are in the middle, and their contrast-stretched differences are on the right. The noise was successfully decreased, but valuable information about the IC lines was also removed, and there could be some information created by AI hallucination. The commercial AI solution used here was trained on general image sets, not specific to IC structures, so improvements are likely possible. The area within the red frame contains as much process-relevant information as the whole image, indicating the possibility of 50 % or higher measurement speed/throughput improvement.

Analysis of acquired information: The CD and overlay measurements, defect detection and classification, and comparisons with references or precomputed results all require extraction, organization, analysis, and formatting for presentation to transform raw data into usable, relevant information and to make process decisions. Completely optimized SEM metrology must have an AI-based solution for this complex procedure because the acquisition relies on and is controlled by the kind and reliability of the information the measurement is about.

Creating image and data sets for AI training, validation, and test: The complete optimization of SEM-based CD, overlay, and defect imaging and measurements requires the generation of relevant AI training, validation, and test images and data sets. Accurate Monte Carlo simulation uses the design or previous measurements or images of the IC structures of interest to create images or data based on signal generation physics. After precomputing these with process-relevant geometry and material composition variations, one can identify the best SEM settings (landing energy, current, dwell time of the electron beam) and the best parameter choices for the detector(s). High-speed analog generation of these can also be used so that image and data segments that belong to repeating structures are "painted in" instead of recomputing already known information. Simple math procedures can add noises, stigma, focus, etc., variations to these images with 100 % repeatability or with known, process-relevant variations of the measurand. This way, optimized imaging and measurements can be done based on firm knowledge and foster the progress of reaching the physics limits of SEMs.

Artificial Intelligence technology will likely revolutionize SEMs and SEM-based imaging and measurements. The quality of the results and new SEM designs will improve significantly. It is vitally important to do this well, even if the progress is gradual and not swift. Sound scientific ideas, and the development of reliable reference image sets for the objective evaluation of AI solutions can aid and speed up progress.