Deep Learning (DL) and Large Language Model (LLM) Applications in Photomask to Wafer Semiconductor Manufacturing

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Company: Advantest Corporation

Product and/or Application

Mask metrology and Mask review system (Revised 2026)
DL and LMM techniques used: Deep convolutional neural networks (DCNNs) and others
Benefits: Processing speed and accuracy for image processing and defect recognition, with optimization for each application. Learning-based approach enables flexible adaption to diverse application and image characteristics with minimum redesign.

Company: ASML

Product and/or Application

Newron Model
DL and LMM techniques used: DCNNs
Benefits: Significantly improves resist and etch model accuracy by capturing additional physical effects missed by conventional OPC models.

Newron SRAF
DL and LMM techniques used: DCNNs
Benefits: Generates SRAF placements based on inverse OPC at full chip application speed, thus significantly improves process window at similar compute cost.

Newron OPC
DL and LMM techniques used: DCNNs
Benefits: Accelerates OPC runtime significantly by reducing the number of iterations needed to achieve convergence.

Company: Averroes.ai

Product and/or Application

Smart Augmentation for Few-Shot Learning
DL and LMM techniques used: Vision Large Language Models (vLLMs), Generative Adversarial Networks (GANs), Diffusion Models
Benefits:

- Context-aware augmentation strategies tailored to domain-specific data (e.g., medical, solar, semiconductor) while preserving semantic consistency via Diffusion Models.
- Utilizing vLLMs as logical elements that help us make contextual augmentation choices that portray the real-world use case.

- Using GANs to automate domain-specific environment transformations to the images as guided by vLLM logical elements.

Automatic Deep Learning Model Architect
DL and LMM techniques used: Vision Large Language Models (vLLMs), Vision Transformers (ViT), Convolutional Neural Networks (CNN)
Benefits:

- vLLM-guided architecture selection (ViTs, CNNs, …) and hyperparameter tuning for optimized performance.
- Automated workflow management (data preprocessing, feature engineering, model evaluation) and explainability for debugging.
- Automated knowledge-based retrieval of image tokenization from relevant pre-trained models for domain-based knowledge transfer.

Deep Learning Advanced Process Control **(New for 2026)**
DL and LMM techniques used: Spatio-Temporal Transformer Neural Network with TabFormer-like signal-wise feature processing, adversarial domain disentanglement, Generative Adversarial Networks (GANs)
Benefits: The framework simulates physical processes and their outcomes using deep neural networks, at its core allowing for virtual metrology and further downstream process control using the surrogate model with reinforcement learning. Our methodology generates expert models that can generalize beyond their equipment and apply to other equipment in the same domain while remaining extremely sample efficient utilizing augmented samples. Our framework also aims to tackle data and target drift by enforcing information bottlenecks that disentangle absolute temporal information from the earlier layers while maintaining relative/short-term temporal patterns information.

Reference-Based Inspection Using Only 1–5 Samples **(New for 2026)**
DL and LLM techniques used: Foundation-scale self-supervised vision encoders, high-dimensional embedding modeling, distribution-aware metric learning, adaptive feature-space distance calibration, few-shot manifold estimation.
Benefits: The framework performs visual validation using only 1–5 reference samples, eliminating the need for large, labeled datasets or predefined defect taxonomies. Instead of supervised classification, the system constructs a compact representation of acceptable structural patterns in a semantically rich feature space, tolerating natural variation while remaining sensitive to subtle structural inconsistencies. An adaptive similarity mechanism learns acceptable dispersion from the minimal reference set, producing calibrated deviation scores without manual threshold engineering. The methodology is domain-agnostic and rapidly deployable. Its ultra-low data requirement reduces collection cost, accelerates time-to-production, and supports scalable inspection across evolving environments without retraining.

Watchdog, Unsupervised Out-of-Distribution Defect Detection **(New for 2026)**
DL and LLM techniques used: Deep convolutional representation learning, unsupervised normality modeling, out-of-distribution scoring.
Benefits: The system learns a representation of normal production conditions using only defect-free samples, then flags deviations outside the learned distribution as potential anomalies, eliminating the need for labeled defect datasets and significantly reducing data collection cost. When deployed alongside a supervised detection model, Watchdog acts as a complementary safety layer, catching novel defect types that fall outside the supervised model's taxonomy while preserving the precision of supervised classification on known defect classes.

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Company: Canon

Product and/or Application

Auto alignment function in lithography tool
DL and LMM techniques used: Convolutional neural networks (CNNs) – VGGNet and transfer-learning are used
Benefits: Reducing unscheduled downtime with judging alignment target image usability, better and quicker than humans.

Image processing and parameter tuning in lithography tool
DL and LMM techniques used: CNNs or region-based convolutional neutral networks (RCNNs)
Benefits: Reducing optimization time and expansion of search area.

Company: CEA-LETI

Product and/or Application

Deep learning for 3D OPC
DL and LMM techniques used: Image-to-image algorithm based on U-Net
Benefits: Generation speed and wider variety of use cases

SEM image denoising
DL and LMM techniques used: Deep learning solution developed internally
Benefits: Accuracy improvement, treatment speed

CD-SEM Digital Twins
DL and LMM techniques used: Image-to-image translation using Generative Adversarial Networks (GANs) and VAE
Benefits: Generation speed, accuracy, adaptability to newer SEM device

Metrology data fusion
DL and LMM techniques used: PCM and/or CNN with data from different metrology tools: AFM, CD-SEM, SAXS, OCD.
DL benefit: Accuracy, reliability, speed

Company: D2S

Product and/or Application

TrueMask® ILT GPU-accelerated, curvilinear full-chip ILT
DL and LMM techniques used: DCNNs and skip-connection (such as ResNet) based U-Net for the image-to-image translation
Benefits: Speeds up full-chip ILT with a better starting point.

TrueMask DLK Quick start DL kit
DL and LMM techniques used: DCNN based deep Autoencoders (AE) for representing images
Benefits: Robust deep learning applications created quickly with neural networks pre-trained for semiconductor manufacturing applications.

CD-SEM Digital Twins
DL and LMM techniques used: Generative Adversarial Networks (GAN), Neural Image Synthesis
Benefits: Enables automated applications that analyze CD-SEM such as defect categorization, model extraction, etc.

Company: DNP

Product and/or Application

Defect classifier from inspection tool
DL and LMM techniques used: Deep convolutional neural networks (ResNet)
Benefits: Improving processing speed and accuracy.

Improvement of pattern detection reliability
DL and LMM techniques used: Generative Adversarial Networks (GANs)
Benefits: Image quality enhancement for reliable CD results.

Operating time prediction for manufacturing and inspection equipment (New for 2026)
DL and LMM techniques used: Gradient Boosted Trees (Machine Learning)
Benefits: Improved equipment utilization and enhanced production scheduling accuracy.

Company: Fraunhofer IPMS

Product and/or Application
Simultaneous contour edge image prediction and SEM image denoising (please refer to https://ieeexplore.ieee.org/abstract/document/9185250 joint paper with Texas A&M University)

DL and LMM techniques used: CNN LineNet2 trained with simulated training data set consisting of 32760 noisy SEM images with the corresponding original images and edge images
Benefits: The method can be useful for real SEM image denoising, roughness estimation, and contour geometry estimation tasks.

Company: Hitachi High-Tech Corporation

Product and/or Application
Semiconductor wafer metrology and inspection system, image and data analysis system
DL and LMM techniques used: DCNNs, etc.
Benefits: Image quality and throughput enhancement for metrology and inspection tool.

Company: Holon

Product and/or Application

Mask metrology system
DL and LMM techniques used: DCNNs, etc.
Benefits: Improving processing speed and accuracy for the measurement of leading-edge masks such as ILT masks.

Company: HOYA

Product and/or Application

Virtual metrology & Defect Classification
DL and LMM techniques used: Deep-neural networks, including image deep convolutional neural networks (DCNNs).
Benefits: Lowering defect identification and classification thresholds, improving processing speed and accuracy, and improving yield.

Company: imec

Product and/or Application

Deep learning for improved process window analysis
DL and LMM techniques used: Autoencoder Neural Network
Benefits: Provides fast proxy for CD metrology defining process window for LS/CH/logic, etc. Improves classification for OPC metrology needs.

Deep learning for defect classification and detection
DL and LMM techniques used: Deep fully connected neural networks, DCNNs, Reinforcement Learning
Benefits: Automatic localization and classification of defects in SEM images enabling enhanced defect inspection for aggressive pitches. Pitch and noise invariant.

Deep learning-based SEM image denoiser
DL and LMM techniques used: Deep fully connected neural networks, DCNNs
Benefits: Unsupervised deep learning training scheme without requiring clean, noiseless images. Denoising reduces noise level only without altering the (real) information; no digital artefacts are introduced. Key process for working with thin resist or enabling contour detection capability.

Deep learning for predicting device electrical performance on metrology data
DL and LMM techniques used: Linear regression, Extra Tree Regressor, SVM
Benefits: Analyzing the overlay data in semiconductor manufacturing and to make use of the overlay measurements from early steps in the process to predict electrical property of the final fabricated structures using machine learning techniques.

Federated machine learning for defect classification and detection
DL and LMM techniques used: Deep fully connected neural networks, DCNNs, Federated ML
Benefits: Proposing a novel FedML framework, developing an improvised weight averaging algorithm against conventional FedAvg, towards supporting defect inspection for real world decentralized dataset from anonymous users.

Deep learning denoiser-assisted framework for robust SEM contour extraction for advanced semiconductor nodes
DL and LMM techniques used: Deep fully connected neural networks, DCNNs
Benefits: Proposing a deep learning denoiser assisted framework for the extraction and analysis of SEM contours with a novel noise removal method, replacing conventional noise reduction techniques (such as Gaussian/Median-blur, etc.) with efficacy in edge extraction accuracy, with minimum/no requirement of external user input or metadata to extract and analyze information from noisy SEM images. An improved contour extraction algorithm capable of extracting contours on the body of noisy raw image itself with a posteriori knowledge derived from its denoised twins.

EDA (Electronic Design Automation) Automation Using Deep Learning
DL and LMM techniques used: LLM (Large Language models) finetuned on Skill code, Verilog/VHDL
Benefits: proposing LLM based framework for automating standard cell placement & routing, modelling circuits as graph structures to predict optimal connectivity, fast power & delay estimation, design rule violation detection, to identify hotspots, OPC corrections and process variations.

Super-Resolution (SR) assisted framework towards increased SEM throughput for defect inspection
DL and LMM techniques used: YOLO architecture with NAS (Neural-Architecture-Search) method integrated with a proposed Super-Resolution branch
Benefits: proposed a SR-assisted framework towards increased SEM throughput ($\sim x8$) for defect inspection, by reduction of required SEM image pixel resolutions. Proposed framework demonstrates improved defect inspection performance/precision for acquired SEM images from different tools (SEM/EDR) and different process steps (ADI/AEI) at lower resolutions/FoV. Additionally proposed novel data augmentation strategies (SEM specific), and their contribution to enhance generalizability and robustness.

GenAI based SEM image generation to address class imbalance and training data insufficiency in advanced node semiconductor defect inspection
DL and LMM techniques used: Diffusion model, inpainting method, DCNNs, etc.
Benefits: Proposed a patch-based generative framework utilizing DDPM towards generating synthetic SEM images while preserving metrology specifications of real images. Defect detector models were trained and benchmarked on these generated synthetic images under different conditions to further validate the applicability of synthetic images within a robust defect inspection framework. Proposed framework can be trained on different processes and their associated defect types concurrently. Proposed framework can generate defect types outside its typical process parameters, to prepare defect detectors for unexpected scenarios, to support defect transfer.

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Company: JEOL, Ltd (New for 2026)

Product and/or Application

Line Width Prediction Tool
DL and LMM techniques used: Gradient Boosting Regression Trees (GBRT)
Benefits: A tool that predicts line width without executing actual pattern writing, helping shorten semiconductor process cycles.

Company: NCS (New for 2026)

Product and/or Application

NDE-MPC Mask model
DL and LLM technique used: Generative Adversarial Networks (GANs) to extract contours from CD-SEM images.
Benefits: Improving the throughput and accuracy of contour extraction.

Company: NuFlare Technology, Inc.

Product and/or Application

SEM defect classifier
DL and LMM techniques used: Deep convolutional neural networks with ResNet, Pix2Pix and Cycle-GANs
Benefits: Speed up the defect analysis and improve the classification accuracy. Defect analysis training, especially for novice experts.

B-SPline Control Point generation tool
DL and LMM techniques used: Convolutional neural network (U-net)
Benefits: Infer control-point positions of unclamped b-spline curve in a shorter time.

Log analysis
DL and LMM techniques used: Natural Language Processing (NLP)
Benefits: Automatically detect the abnormalities from log and predicts upcoming drawing errors.

Beam drift Prediction
DL and LMM techniques used: Long short-term memory (LSTM)
Benefits: Improve mask drawing quality with automatic abnormal search and prediction.

Equipment health check and Prediction
DL and LMM techniques used: Long short-term memory (LSTM)
Benefits: Automated and fast analysis with over 100 measured parameters.

Company: Siemens Industries Software, Inc.; Siemens EDA

Product and/or Application

Calibre Neural Network Assisted Modelling
DL and LMM techniques used: DCNN or DNN for predicting, post exposure, post development and post etch contours
Benefits: Improves accuracy as well as predictability of the models.

Calibre Machine Learning OPC
DL and LMM techniques used: Deep Neural networks with supervised learning for speeding up OPC
Benefits: Improvement in OPC speeds.

Calibre Machine Learning for SEM Image Processing
DL and LMM techniques used: DCNN for contour extraction, image filtering, and image pre-processing
Benefits: Improved accuracy contour edge detection and contour extraction robustness.

Calibre Monotonic Machine Learning
DL and LMM techniques used: Feature vector driven neural networks for speedup of ILT for main features and SRAF insertion
Benefits: Significant speedup of ILT.**Calibre LFD with Machine Learning**
DL and LMM techniques used: Neural networks and data enrichment techniques for yield-limiters detection in the design flow
Benefits: Order of magnitude speedup and improved coverage over standard techniques that result in improved design yield and reliability.

Calibre Wafer Defect Engineering with Deep Learning
DL and LMM techniques used: Feature vector driven neural networks for layout analysis and hotspot detection
Benefits: Robust applications that speed up test chip development and improves yield and reliability in the fab by quickly and efficiently detecting yield limiter.

Calibre Fab Design Process co-optimization
DL and LMM techniques used: Fab data anchored data enrichment with GBT (Gradient Boosted Tree)
Benefits: Robust handling of sparse fab metrology and inspection data. Fast feature importance ranking driving multivariable optimization.

Company: STMicroelectronics

Product and/or Application

Fab Digital Twin - automatic defect classification (ADC)
DL and LMM techniques used: CNNs
Benefits: Corrective action in real time and defects are caught before other processes are added.

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Company: Synopsys

Product and/or Application

Proteus Modeling
DL and LMM technique used: DCNNs to enhance resist and etch
Benefits: Improved model quality with faster time to results.

S-Litho Modeling
DL and LMM technique used: CNN training based on synthetic rigorous data.
Benefits: Full-chip speed capability based on predictive Resist 3D rigorous models for resist height, resist contours at various Z-Levels and stochastic failures.

Proteus Lithography Proximity Correction
DL and LMM technique used: DCNNs
Benefits: Fewer correction iterations for faster convergence with comparable QoR.

Proteus AF Placement
DL and LMM technique used: DCNNs
Benefits: Fast full chip curvilinear AF placement for improved wafer quality.

Proteus Litho/Etch Hotspot Detection
DL and LMM technique used: DCNNs
Benefits: Improved detection of litho and non-litho related hotspots with comparable TAT.

Company: TASMIT

Product and/or Application

Semiconductor wafer metrology and inspection system (Revised 2026)
DL and LMM technique used: Combination of DCNNs and ACM (Active Contour Model)
Benefits: Developed an advanced contour extraction method that integrates Active Contour Model with deep learning capable of accurate contour extraction of underlayer patterns from see-through BSE images.[1,2,3]
[1]M. Oya et al., "Utilization of active contour model with 3D-SEM simulation for see-through BSE image of high voltage SEM", Proc SPIE 129550R (2024)
[2]M. Oya et al., "Advanced pattern contour extraction function for see-through BSE images of high voltage SEM", Proc SPIE 134626 (2025)
[3]M. Shinji et al., "Occlusion-aware pattern measurement for see-through BSE images of HV-SEM via contour- and pixel-based approaches", SPIE AL 13981-145 (2026)

Semiconductor wafer metrology and inspection system (Revised 2026)
DL and LMM technique used: DCNNs for image denoising and super-resolution
Benefits: Developed a novel denoising algorithm which is based on Noise2Noise but is specialized to train the artificial SEM noise. Improvement of the roughness measurement precision of the proposed method compared to the deep denoise model trained using simple artificial noise has been confirmed.[4]
[4]T. Mori et al., "High-performance denoiser based on deep learning trained by precisely reproduced SEM noise", Proc SPIE 120531D (2022)

Semiconductor wafer metrology and inspection system (Revised 2026)
DL and LMM technique used: Extremely Randomized Trees (ERT) technology for the SEM contour extraction
Benefits: The accuracy and the precision of EPE measurement using the contour extracted by proposed method are improved.[5]
[5]Y. Okamoto et al., "Contour extraction algorithm for edge placement error measurement using machine learning", Proc SPIE 113252A (2020)