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AI in Semiconductor Industry

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Abstract

This introductory article opens the “Applications of AI in the Semiconductor Industry” section by giving a holistic overview of the development of artificial intelligence (AI) technologies applied to the industry. Historically, the semiconductor industry has utilised complex automation for many tasks and areas, especially in repetitive work and uniform processes. The high need for flexibility in manufacturing, increased diversification of products, complexity, and demand for more autonomous operations, including human-machine interaction, have led to a strong push towards using AI technologies in semiconductor manufacturing. AI technologies are applied in semiconductor product development, digitised product definition (DPD), knowledge management system for risk assessment and root cause analysis, image recognition for inspection and defect classification in front end (FE) and back end (BE) applications for anomaly detection in process chains. Deep learning (DL) and Machine Learning (ML) techniques have given a new stimulus to semiconductor industry research to address the unique challenges for semiconductor manufacturing as the technologies nods are evolving and the number of process parameters to be controlled is increasing. In the end, the article introduces the four contributions to this section, highlighting the use of AI, computer vision, neural networks (NNs) in various use cases in semiconductor manufacturing processes.

Keywords: artificial intelligence (AI), industrial artificial intelligence, semiconductor industry, manufacturing, image processing, computer vision, neural networks, pattern recognition, natural language processing.

2.0.1 Introduction and Background

Industrial AI integrates domain-specific know-how with the AI-based functions and capabilities into various AI-enabled applications in industrial sectors. AI technologies applied in the industry enables and accelerates the autonomous and semi-autonomous processes that run those operations, realising the vision of the self-optimising manufacturing facilities. AI plays a double role in the semiconductor industry: it acts as a key leverage element for digitising the manufacturing processes and provides the technology for semiconductor manufacturing to optimise the operations and control the process parameters as the technologies advance toward nanometre-scale semiconductor nodes. The primary goals of using AI technologies are to reduce costs, save time, improve quality, and increase the robustness of industrial processes. AI technologies are applied to increase the efficiency and effectiveness of industrial processes by mastering complex situations within the limitations of specified systems. The use of AI in industrial sectors represents a new opportunity for industrial stakeholders to optimise resources and increase profitability with a high economic impact.

Semiconductor companies are integrating AI, ML, expert systems, and other technologies to develop intelligent manufacturing environments to transform scheduling, dispatching, equipment productivity, process and equipment control, and robotic management. These technologies optimise quality, productivity, efficiency, and flexibility while maximising cost-effectiveness and accelerating overall innovation.

2.0.2 AI Developments in Semiconductor Industry

Today, the semiconductor manufacturing processes are based on the use of Advanced Process Control (APC) techniques. The availability and use of custom, off-the-shelf APC facilities in FAB are part of the production requirements. SEMI consortium [10] has issued the “The Process Control

System Standards" (SEMI E133) that defines communication between components to enable run-to-run (R2R) control, fault detection (FD), fault classification (FC), fault prediction (FP) and statistical process control (SPC). It is supported by SEMI specifications E125 and E134 on EDA (Equipment Data Acquisition).

The APC remains a fundamental pillar in semiconductor manufacturing supported increasingly by AI and Industrial Internet of Things (IIoT) technologies.

Today, the semiconductor manufacturing facilities experience more challenges due to high-mix/low-volume loads that result in shorter production cycles and frequent product mix changes, with increasing pressure on costs and quality.

In addition, the effect of Moore's law is expected to approach the limit of possible performances. Moore's law has been seen as the fundamental driver for innovation in the integrated circuit (IC) industry. The doubling of IC performance started to slow down due to the physical limitations of transistor shrinkage and quantum mechanical effects such as "quantum tunnelling" [1][2], which posed many challenges due to excess heat generation and power consumption. The phenomenon of "dark silicon" has posed other problems concerning the performance-cost perspective.

The development of new semiconductor technologies requires complex manufacturing facilities with advanced metrology systems. Each aspect of semiconductor processing, from lithographic design rule specifications to continuous yield analysis, essentially depends on accurate and reliable data for critical dimension (CD) lithographic patterning and material composition. The status of semiconductor metrology techniques and the opportunities for AI methods to provide the necessary breakthroughs to support future process node development is presented in [8][9].

The competitive pressures on semiconductor manufacturers are increased to reduce production time and costs, improve quality, shorten innovation cycles, and accelerate new technologies' ramp-up [3].

A list of few significant advances made by AI and IIoT in the semiconductor industry is presented below:

Analytics and optimisation used to eliminate repetitive processes and searches in content management for root cause analysis. Expert systems for root cause failure analysis and risk assessment in semiconductor production help access knowledge across all related content and support transferring domain knowledge from engineers' expertise into algorithms. Fast and reliable decisions are made using documents' data sources (e.g., failure mode effect analysis, etc.). Performance improvement is made possible by performing multidimensional correlations analysis using highly nonlinear data through machine learning and deep learning techniques and discovering correlations where human experts need time and are prone to errors.

Sensing used in automated quality assurance by integrating AI-based capture systems such as image recognition to support the visual inspection and classification of defects at both the front-end (wafer fabrication) and back-end (assembly and test) manufacturing processes. Manual and other conventional quality inspections are unreliable, expensive, have a low detection rate, and are challenging to scale. The use of AI technologies increases the reliability and efficiency of these processes.

Packaging optimisation used to improve the assembly and packaging processes in the industry by applying AI solutions consisting of a combination of anomaly and deviation detection to increase reproducibility.

Digitalising product definition integrating AI technologies used to optimise the relationship between requirements and constraints. The complexity of the requirements stack requires optimisation techniques that AI provides. Significative development is expected by using AI integrated into manufacturing facility infrastructure to support the transition from document-based requirements to machine-readable formats.

2.0.3 Future Trends for AI Technologies and Applications in Semiconductor Industry

The global semiconductor market is projected to grow from $452.25 billion in 2021 to $803.15 billion in 2028 at a CAGR of 8.6% during 2021-2028 [4]. Globally, the long-term market trend for electronic components is expected to exceed US $1,000 billion by 2030. It is estimated that the research and development costs of developing circuits from a 65 nm node to a state-of-the-art 5 nm node have increased from $28 million to $540 million, and fab build costs for the same nodes have increased from $400 million to $5.4 billion [5]. By implementing AI and ML alone, the industry can gain $35-40 billion annually. Over a more extended timeframe of 3 to 4 years, it could double to almost 20% of the industry's current revenue [5].

AI is transforming the industrial semiconductor industry, moving from an "application-centric world" to a "data-centric world", where almost all data will be generated and consumed by machines. The industry's growth is no longer limited by the ability of humans to create or consume data. New computing approaches emerge from processing the massive amounts of available data, and AI-based hardware and software are required to enhance productivity. Training AI computing becomes incredibly energy-intensive, so the industry must drive performance-per-watt improvements [6].

The AI technologies can be used to adjust tool parameters to achieve greater accuracy by deploying real-time tool-sensor data, metrology readings, and tool-sensor readings from earlier process steps, enabling ML algorithms to capture nonlinear relationships between process time and outcomes (e.g., etch depth). The data aggregated could include electric currents in the etching process, light intensity in lithography, and temperatures in baking. Optimal process times based on AI models can be provided for individual wafer or per-batch that decrease the processing time, improve yield, or both, thus reducing the cost and increasing throughput.

Computer vision and AI algorithms show their capabilities in the visual inspection of wafers to ensure quality by detecting defects in the front-end and back-end production process using cameras, microscopes, or scanning-electron microscopes. Optical inspection in the semiconductor manufacturing process for analysis and verification represents an area with considerable potential for AI research and can significantly improve the equipment's expected performance. In addition, combining different physical and electrical characterisation and measurements techniques with data mining and AI can provide better yield curves. AI-based wafer-inspection systems using DL and computer vision are trained/learned to automatically detect and classify defects on wafers with better accuracy than human operators. The use of dedicated hardware-based on graphics- and processing tensor-processing units and on-premises edge computing enables computer-vision algorithms to train and deploy in real-time in a scalable manner.

AI-based analytics can support the *automated yield learning in integrated circuit design and optimise* the iterations based on feedback from manufacturing. Deploying ML-based algorithms to identify patterns in component failures, predict likely failures in new techniques, and propose optimal layouts to improve yield and increase the design's efficiency.

2.0.4 AI-Based Applications

AI4DI partners [7] are developing AI and IIoT technologies with applications in different areas of the semiconductors sector. The articles included in this section cover four demonstrators and actionable insights into how AI and

IIoT are used in semiconductors applications, presenting challenges and technological advancements to accelerate the digitising process across the industry.

The article *"AI-Based Knowledge Management System for Risk Assessment and Root Cause Analysis in Semiconductor Industry"* proposes a new expert system concept for root cause failure analysis and risk assessment in the semiconductor industry. The knowledge representation of the expert system's main component is based on knowledge graphs created with knowledge extracted from various data sources and post-processed for better consistency. Queries to the expert system will provide known real-time risks of the production flow in semiconductor manufacturing. The paper concludes that integrating fast-developing natural language processing technologies and AI/ML methods seems the most promising way to digitalise FMEA documents and create this expert system that can support FMEA experts at their more complex tasks. Research conducted in AI4DI is also working toward accommodating industrial environment specifics to facilitate the integration of the FMEA tool in the real environment of industrial semiconductor manufacturing.

The article *"Efficient Deep Learning Approach for Fault Detection in the Semiconductor Industry"* investigates the use of high quantized artificial neural networks to be implemented on small industry-grade microcontrollers enhanced with hardware accelerators. The system proposes an automatic visual inspection and classification of defects in both the front- and back-end manufacturing processes in the semiconductor industry to increase yield and reduce costs. This is a considerable improvement of the current inspection performed by humans, primarily because of the high throughput in the production lines. Preliminary experiments indicate that when appropriately trained, quantized artificial neural networks can reach high accuracy, and their implementation using the interconnection of two hardware parts can be resource-efficient. It remains to be seen for the following steps to be applied on a larger scale.

The article *"Towards Fully Automated Verification of Semiconductor Technologies"* proposes an extension of the existing workflow with an automated device cross-section analysis to increase trust in semiconductor devices and their originality (i.e., combat rogues). Central to this approach is the confluence of knowledge from human domain experts and AI/ML experts input to automated image interpretation. The goal is to extract technological attributes and verify them against original design and specifications. By applying state-of-the-art AI, the results are comparable to those of an operator's manual effort.

The article *"Automated Anomaly Detection through Assembly and Packaging Process"* highlights the importance of continuous optimising, using, and adjusting the assembly process in the semiconductor industry to achieve competitive advantages, mainly as its reproducibility depends on various distributed parameters. This demands the high accuracy of employed automatic inspection tools for visual defect detection. An AI solution consisting of a combination of anomaly detection (unsupervised learning) and supervised learning for detecting deviations is proposed, satisfying the demand, and required features. Two anomaly detection examples have been considered, and the results showed potential to be good alternatives to classical approaches.

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