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IT@INTEL

Faster, More Accurate Defect Classification Using Machine Vision

Intel has achieved greater accuracy with a broader range of classification types using machine vision defect classification.

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Executive Overview

With the significant investments that companies make in new manufacturing technology and processes, defect detection and classification are critical. Many of these companies are creating products used in vehicles, medical devices, and safety tools, requiring a high degree of quality and reliability. By identifying and correcting problems early, businesses accelerate return on investment and increase manufacturing productivity. Yet many manufacturers rely on manual visual defect classification, which can be slow, labor-intensive, inconsistent, and often inaccurate, resulting in higher costs. Moreover, perceiving certain defects through manual visual inspections is beyond the ability of humans.

Highly sensitive automated defect classification (ADC) using machine vision (MV) and machine learning (ML) can increase early defect detection and improve classification accuracy and consistency. This allows factories to rapidly identify and correct defects to maximize machine capacity and process high-quality products.

At Intel, we use MV and ML in a variety of manufacturing use cases, some of which are quite complex. During fabrication, we collect images from multiple channels and compute thousands of features ranging from standard shape descriptors to sophisticated informative pattern attributes that are used not just for defect classification, but also to provide insights into mechanisms generating specific defect modes. The high-volume ADC solution we developed for wafer fabrication uses Intel® Xeon® processors and has resulted in greater accuracy with a larger number of classification types. We also use MV and ML to repurpose existing images and identify defects in our assembly and test factories. Our ADC solution has delivered the following benefits at a scale and level of accuracy that we could not have achieved even with the most experienced technicians:

- Faster insights into manufacturing process health
- Quicker identification of root causes for specific issues
- Greater improvement in yield

We are now able to measure and classify most of the wafers that Intel's factories produce with a higher degree of accuracy, without increasing our total cost of ownership (TCO) or requiring specialized skills and training.

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Acronyms

ADC	automated defect classification
CV	computer vision
HPC	high-performance computing
ML	machine learning
MV	machine vision
SEM	scanning electron microscope

Background

Inline defect metrology helps detect excursions and catch issues in microscopic silicon chip layout before they become more serious. Minute quality fluctuations from the optimum design baseline frequently predict process health. Identifying problems with tools and processes early helps identify trends versus random occurrences, which can prevent waste and allow manufacturers to take corrective action. Defect classification can help pinpoint issues at their source; for example, it can detect whether an excursion in the paint coat of an automobile is due to problems with the color mixing or application tool. But manual defect classification is labor-intensive, time-consuming, and can create a bottleneck in manufacturing processes.

Based on our experience, it can take 6-9 months to train people to manually classify defects with 90 percent accuracy. And even after training is complete, an expert operator typically maintains only 70-85 percent accuracy over time (see Figure 1). Some of reasons for this decline include:

- **Highly repetitive work.** Image classification can account for up to 80 percent of workers' time. The repetitive nature of the task can become mundane, making it difficult to motivate workers.
- **Lack of insight.** Manual processes, as well as repetitive and tedious tasks, often do not provide technicians with perspective of the benefits that accurate defect classification provides, further eroding worker motivation.
- **Process advancements.** As technology changes, so do the processes that rely on it. Process advancement often leads to more complexity, more types of classifications, and more repetitive work.
- **Difficulty in classifying.** Many defects are difficult to classify simply by looking at them. In fabrication, process layers and the physical location of a defect on a wafer can require precision and design cross referencing to accurately diagnose. Furthermore, some defects simply cannot be perceived by the human eye and brain.

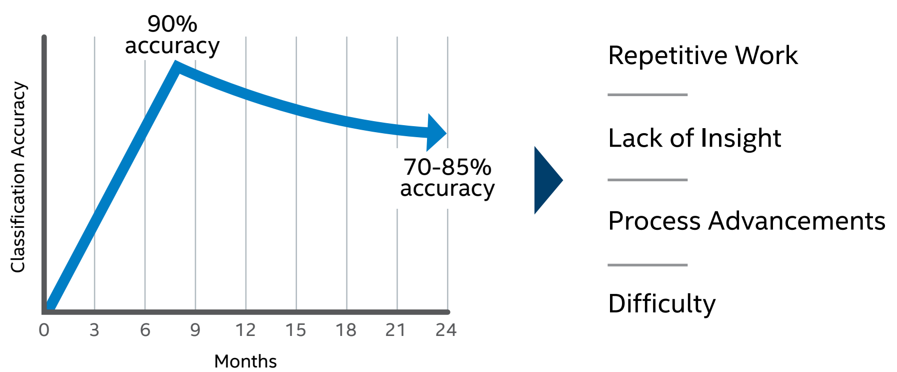

Figure 1. It can take 6-9 months to train technicians to manually classify defects with a 90 percent rate of accuracy. Due to the changing, repetitive, and difficult nature of the work, accuracy levels typically drop to 70-85 percent over time.

As new technology emerges, the demands for image classification have grown to a level that can no longer be achieved through manual methods. Automated defect classification (ADC) using machine vision (MV) and machine learning (ML) can help. MV-based ADC can improve speed, consistency, and efficiency in manufacturing processes.

Solution

At Intel, we have implemented several use cases for MV- and ML-based ADC using Intel® Xeon® processor-based servers. Our high-volume ADC solution in wafer fabrication uses scanning electron microscope (SEM) photos as high-resolution image sources for our ML-based ADC algorithms. But beyond wafer fabrication, we also repurpose existing images that were originally taken for other reasons in the test and assembly factories to classify defects introduced during the packaging.

Using MV in Wafer Production

In our wafer-manufacturing facilities, our ADC with MV and ML solution classifies thousands of defects per hour, but it goes beyond accurate classification of problems. Defects have special structures, patterns, locations, and other features with respect to layout and design. The solution includes:

- **Root cause analysis and reverse engineering.** We provide options to engineer informative features against hundreds of structures, calculating thousands of features in real time on the CPU. These calculations can be used to conduct root cause analysis by reverse engineering functions in the models.
- **Automatic feature learning.** Where a black-box defect classification system is needed, we can provide automatic feature learning options ranging from traditional MV defect mask descriptors to deep learning-based, convolutional neural network (CNN)-based, and more advanced and complex techniques.
- **Data classification.** Classification models at each layer draw on worldwide defect metrology domain experience to categorize vast amounts of historical data to train models. Preprocessing this data includes identifying the technology, manufacturing process, layer, and product.
- **Defect classification.** Classification models categorize defects based on a predefined level of certainty. When the model does not achieve this level of certainty, defects are manually classified and used to retrain the model.

Machine Vision Versus Computer Vision

The term machine vision (MV) is a subset of computer vision (CV) that focuses on industrial applications in discrete and process manufacturing as well as non-industrial applications, such as surveillance and medical imaging. Industrial applications focus on the factories and address the following:

- Quality assurance and inspection
- Positioning (often with robots)
- Measurement
- Identification

CV and MV often use the same basic components of sensors, lighting, compute machines, and image-processing software.

Taking Advantage of Existing Assembly Equipment

We also use MV and ML to classify defects in post-wafer manufacturing by taking advantage of existing imaging tools that were originally designed for other purposes, such as unit alignment. By repurposing standard images used for alignment and other uses, and with processing programs running on the equipment PC, we can identify additional defects, such as staining from problems with the epoxy application tool or excursion related to ball application (see Figure 2).

For some use cases, we can now identify and classify defects in the assembly process where we previously did not conduct any defect classification, without purchasing new equipment or investing in major upgrades to existing equipment. We have significantly improved yield by identifying problems earlier, leading to increased return on investment (ROI) for these existing tools. The solution also provides a more reliable and consistent process of identifying defects, allowing employees to focus on other important tasks.

Refining the Models

In our wafer fabrication factories, we classify thousands of defects per hour, and we use tens of thousands of defects to train the models. During wafer fabrication, when a classification does not meet the required level of certainty, it is referred to the operator to manually classify it. The manual classification augments existing labeled data and is used to train the relevant ML model. The control limit certainty can vary per product-fabrication layer, depending on actual factory performance. For example, if defects are consistently found in a specific layer of the wafer, the process engineer can raise the certainty level to send more images through manual classification and refine the model. The classification certainty represents the ML confidence score for a specific classification.

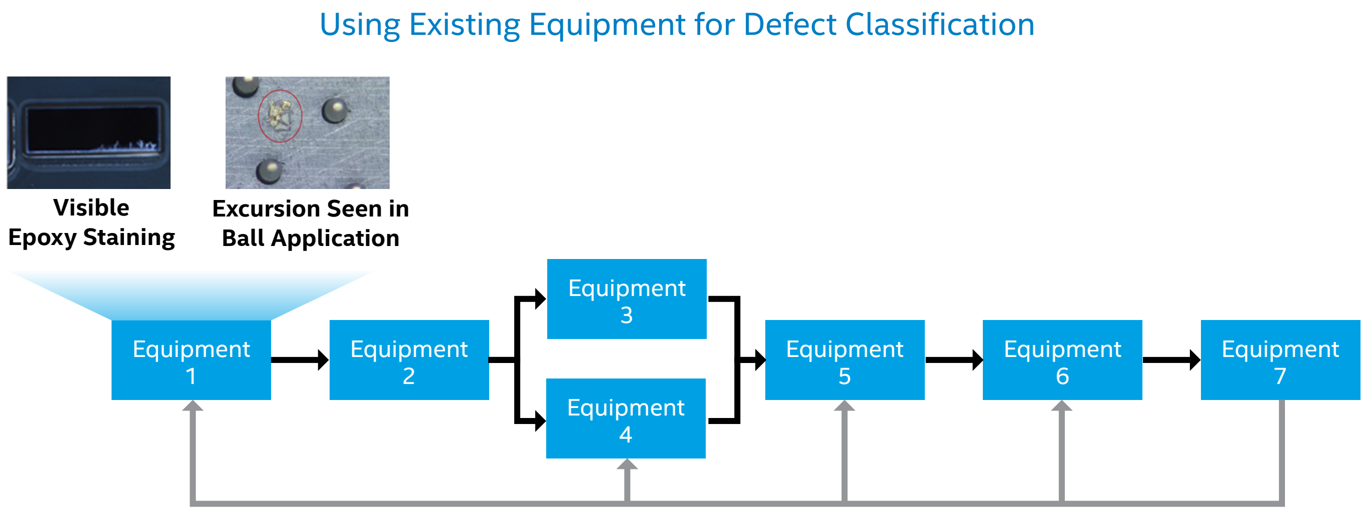

Figure 2. We use imaging equipment designed for other purposes, such as improving alignment, to classify defects. For example, staining is visible when there are problems with the epoxy application and some defects are visible during the ball application process.

Results

With ADC, we can now measure and classify most of the wafers produced by Intel's factories with a required rate of accuracy. We have found that any defect that we can manually classify with SEMs can now be accurately classified using ADC with ML and MV. We have not experienced any increase in the total cost of ownership (TCO) over other solutions. The solution, once deployed to production factories, is maintained by Manufacturing IT and has not required specialized skills and training.

By using existing imaging equipment in the post-wafer manufacturing process, we have also been able to implement MV- and ML-based ADC where it did not previously exist, preventing errors early and increasing the yield at no additional cost.

Architecture

Our ADC with MV and ML solution uses Intel Xeon processor-based servers for both classification inference and model training. Each classification system can run continuously without additional support costs. Intel Xeon processors provide workload-optimized performance and throughput for advanced analytics and high-performance computing (HPC) applications.

Using a PC connected to the tool, collected images are sent to classification servers and supervised ML models—one model per product fabrication layer. The images are labeled and defects are categorized, and then returned to the tool PC, which sends them to the analysis datastore for analytics (see Figure 3). Labeled images are also sent to the model-building servers where models are retrained with new information before they go to the production-classification inference servers. All hardware is scaled to achieve parallel distributed processing for data extraction and model training.

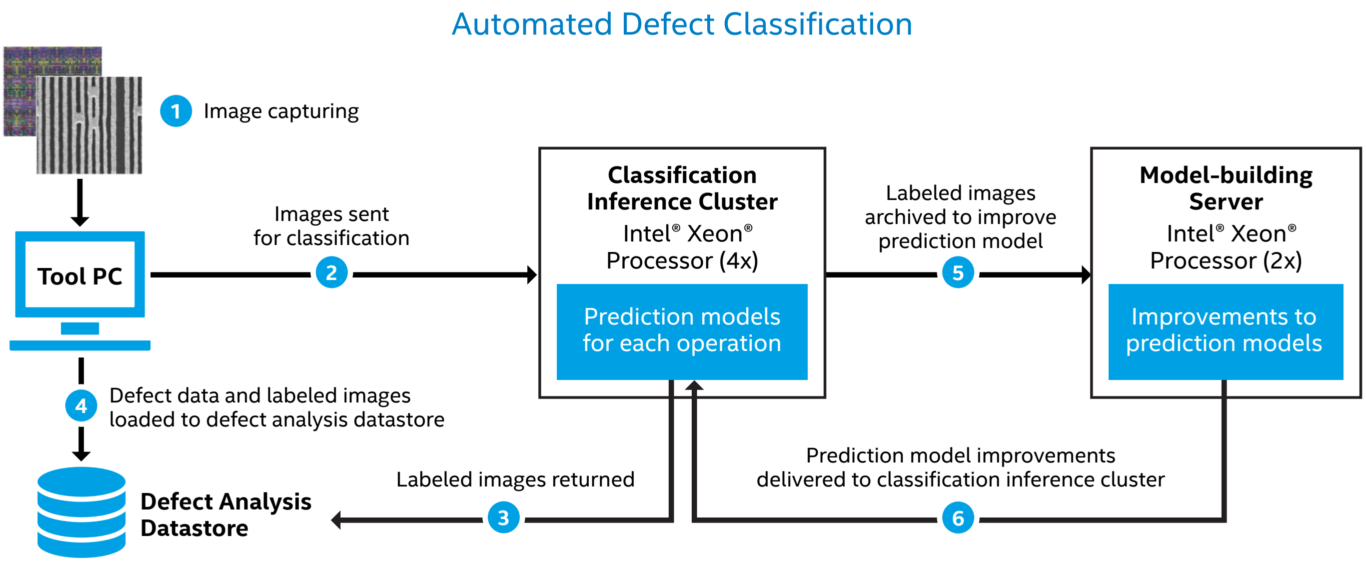

Figure 3. The automated defect classification (ADC) solution with machine vision (MV) uses Intel® Xeon® processor-based servers for both the production-classification and model-building servers.

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Conclusion

Manual visual defect classification is labor-intensive and repetitive, taking up to 80 percent of workers' time. Also, results from manual vision inspection are not consistent from person to person. It can also be difficult to motivate workers to focus on defect classification, leading to lower accuracy rates. Furthermore, some defects cannot be classified at scale by people due to the limitations of the human eye and brain. Automatically detecting defects and properly categorizing them using MV and ML allows manufacturers to address tool and process problems early and establish comprehensive real-time process control.

Intel's high-volume ADC solution based on MV and ML uses Intel Xeon processors to build accurate classification models that categorize thousands of defects in real time. Using worldwide defect metrology domain experience, we train and retrain our models, resulting in greater accuracy, a broader range of classifications, and workload consolidation without requiring specialized skills and training. We are also able to identify the source of the defect using commonality analysis, enabling the advancement of the Intel manufacturing process.

Similar technology can be used in many different industries—wherever machines capture images, regardless of the original use for those images. When used as inputs to ADC, these images can help identify otherwise overlooked defects in a timely, consistent, and accurate manner.

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