PHOTOMASK

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Lithography tool improvement at productivity and performance with data analysis and machine learning

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ABSTRACT

Semiconductor manufacturing equipment must maintain high productivity and provide high-yield processing and Canon has developing high-reliability exposure tools that have demonstrated high-uptime and performance stability in production. As global emergency epidemic restrictions limit the travel of expert engineers, customer service becomes more challenging and alternative methods of support are being developed to help customers meet their production roadmaps.

To help control performance, lithography tools have sophisticated logging systems that can monitor every movement in the tool and we studied a novel Artificial Intelligence system that utilizes big logging data to help improve exposure tool uptime, productivity and performance related to yield.

One goal of our study is to minimize exposure tool downtime by monitoring and reacting to tool status. For this purpose we are applying machine learning to develop abnormality detection or prediction models with automated recovery procedures for each abnormality. We will report on Auto-Fault-Tree-Analysis (FTA) models being constructed to evaluate large volumes of design and trouble information to help minimize downtime.

Another study goal is to improve lithography tool performance by monitoring and reacting to factors including overlay accuracy and CD uniformity that can strongly affect device yield. Outputs of this analysis include simulation and optimization of equipment performance, and virtual metrology.

This paper reports on the system we are developing to help increase the uptime, productivity and imaging performance of Canon semiconductor lithography tools. The system is designed to monitor the operating state of lithography tools and apply automated recovery and optimization actions identified through machine learning.

1. Introduction

To create innovative lithography tool value, we dramatically improved service with digitalization solutions, data collection and analytics[1][2].

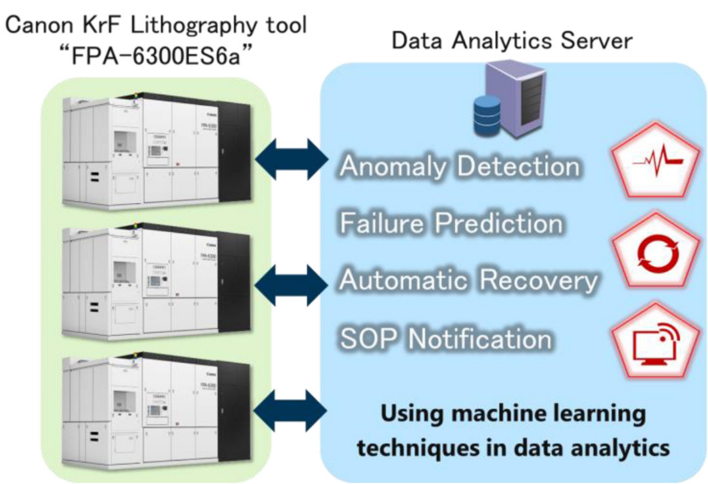

Figure 1. Data Analytics Server on customer's Fab.

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EDITORIAL

Travelling to Photonics West 2022

Jan Hendrik Peters, bmbg consult

It has been a long time since we all have been staying at home for work. Now that vaccination again allows international travelling, it is a great experience to be back and personally meet people for business. For me, it all started with SEMICON Europa last November in Munich where I had a booth as part of the Silicon Saxony exhibition area. Despite the lower number of visitors at the show and stopping by at my booth, the quality of each of these contacts has been much better than for previous exhibitions.

But the real travel highlight was the journey to San Francisco to join the Photonics West Exhibition in January of this year. It was my first trans-Atlantic travel to the same location and event as for my last international trip in early 2020. And it was good to be back on site and just walk through the exhibition and spontaneously talk to people who had an interesting exhibit or display. Despite the smaller number of booths compared to 2020 and about half of the visitors, all people I talked to were very satisfied with the quality of the contacts they had. SPIE had organized several industry sessions in the exhibition hall which were well attended and provided deep insights into some of the fields.

I was especially impressed with the talks around quantum sensing, quantum networks, and quantum computing, and enjoyed finding several companies active in those fields on the exhibition floor. Some of the presentations of the **Quantum West** session have been recorded and will be made available in the SPIE Digital Library, as I learnt from SPIE. There has been quite some progress in this field, not only in the technology itself, but also in the understanding of what kind of ecosystem needs to be set up to get a viable business. This ranges from the development of the so called "no trust" capable equipment for secure communication networks (sending and receiving entangled photons) up to the growing awareness that quantum computing at industrial scale will only be possible if the best-known production practices are applied also to this area. This, in my view, holds true for all the current different approaches from neutral trapped atoms to photon-based solutions.

The other section I liked very much was the 2022 SPIE **Startup Challenge**, where young companies, after going through an investor pitch training program, presented their products to a jury and the exhibition visitors. There are some really great ideas, technologies, and products out there with very engaged young entrepreneurs, many of whom I am sure will be successful in the long run.

From my point of view, it is quite interesting for mask makers to dive deeper into all these new exciting application fields, to better learn about special requirements for this sector. There may be some new customers out there for us with some challenging business, especially in the area of fully integrated photonics circuits.

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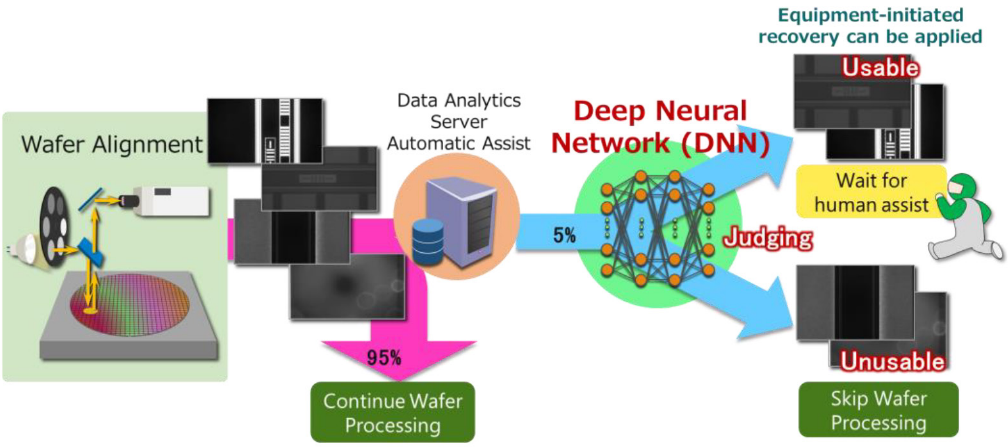

Figure 2. Alignment system in lithography tool, automatic recovery or image classification with DNN on Data Analytics Server.

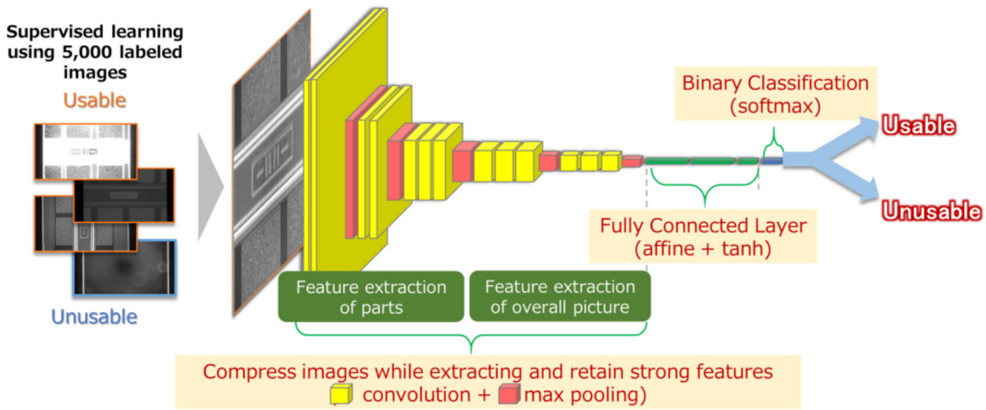

Figure 3. VGG model.

Our digitalization solutions began with:
- Automatic recovery
- Anomaly detection
- Abnormal prediction
- Improve equipment utilization
- Performance simulation
- Remote support capability

We have built a data analytics server on our customer's Fab, which connects with multiple Canon "FPA-6300ES6a" KrF lithography tools. As shown in Figure 1, for the purpose of reducing unscheduled downtime, digitalization solutions such as anomaly detection, automatic recovery, trouble and standard operation procedure notification have been deployed to the Data Analytics Server.

In semiconductor manufacturing, defect detection and parameter optimization using big data analysis and machine learning technologies have been enthusiastically researched these days[3][4][5]. In our Data Analytics Server as well, a large amount of data in lithography tool is acquired in real time, and analyzed with various statistical calculation method, including machine learning techniques.

2. Alignment Image Detection Improvement Using Deep Learning

2.1 Alignment system

The lithography apparatus detects the alignment marks patterned on the wafer and performs overlay exposure. The alignment mark is detected by recognizing the image data acquired by the scope. The alignment marks are detected by template matching for high-speed mark detection.

But mark detection sometimes fails due to the influence of device patterns and noise. When the tool goes down during mark detection, Data Analytics Server can automatically execute a recovery instruction on the tool, and the tool can be restored by recovery processes such as mark search drive and optimization of measurement system and image filter conditions.

In most cases when the tool goes down during mark detection, automatic recovery processing can restore the tool, but about 5% of the recovery processes will fail. In such a case, the image recognition processing by the deep neural network (DNN) is executed.

The measured mark image is classified as detectable by DNN and usable, or the mark is not detected and is unusable. The goal is to judge alignment mark image usability faster and more accurately than humans to help reduce unscheduled downtime. If the marks are determined to be usable, the tool waits for human assist and equipment-initiated recovery can be applied. If the marks are determined to be unusable, the wafer processing is skipped.

Figure 2 illustrates alignment system in lithography tool and automatic recovery instruction or image classification with deep neural network in Data Analytics Server.

Therefore, classifying alignment marks as usable or unusable with high accuracy can help reduce unscheduled downtime. This time, we used a VGG convolutional neural network model, which is one of the most popular models in image recognition. We prepared around 5,000 labeled images and executed supervised learning.

The VGG model is illustrated in Figure 3 and consists of multiple convolutional layers, pooling layers, and fully connected layers. The first few CNN layers learn part-level features, and remaining CNN layers learn the overall pictures features. Then the images are compressed while

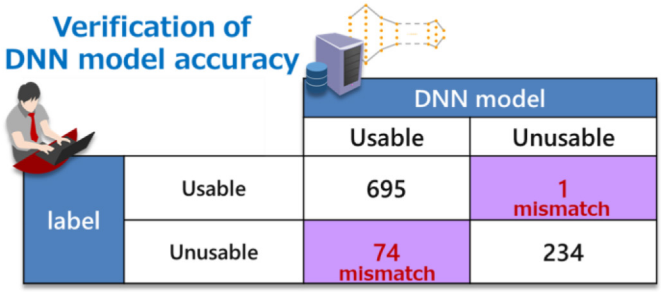

Figure 4. Confusion matrix for verification of DNN model accuracy.

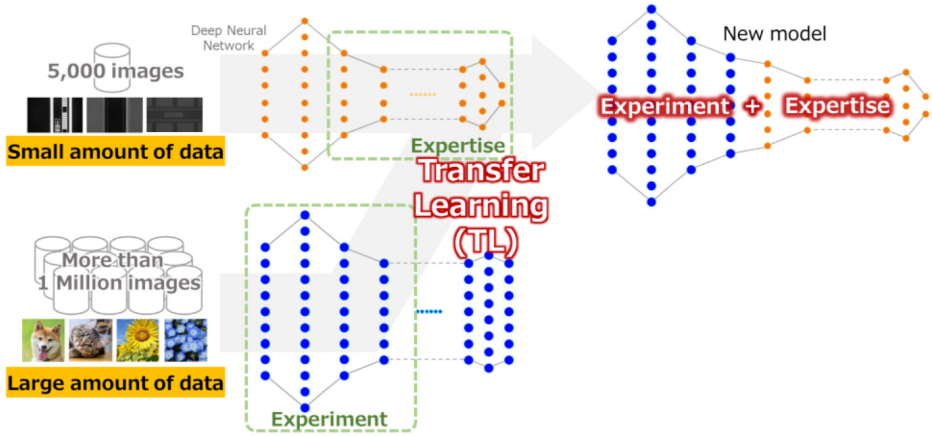

Figure 5. Transfer learning model.

extracting and retaining strong features. Finally, the model will learn to judge usable and unusable mark conditions by binary classification.

2.2 DL model and accuracy

5,024 alignment images are not enough for Deep Learning. So for the purpose of verifying the generalization of constructed mode, we used cross-validation. In cross-validation, datasets for training and testing are prepared separately using 5 patterns of division methods. Then, the model with the highest accuracy in the test data is selected as the model with the best general performance.

Figure 4 illustrates the confusion matrix for verification of DNN model accuracy. 1,004 images were used for verification. The accuracy of usable images was 99.9%, accuracy of unusable images was 76.0%, and the total accuracy of all images was 92.5%. Although the accuracy of usable images was high (only one image was mismatched), the first result is not sufficient because the accuracy of unusable images was low. Further improvement is necessary.

Therefore, we examined improvements by various methods such as data augmentation and ensemble learning of other DL algorithms. Finally, we chose transfer learning and fine tuning as the models with the best accuracy method.

Figure 5 illustrates the transfer learning. Before learning using the small amount of alignment image data, we transferred a part of the DL model that learned a more than 1 million animal and plant images. Transfer learning combines the experience gained by learning large amounts of data with fine tuning expertise to achieve a particular goal.

Figure 6 illustrates the confusion matrix for verification of transfer learning model accuracy. Accuracy for unusable image improved to 92.9%, and total improved to 97.3%. This high mark detection accuracy has helped reduce lithography tool unscheduled downtime.

3. Anomaly Detection of Coolant System

3.1 Anomaly detection merit

Figure 7 illustrates a simple example in which lithography tool performance gradually deteriorates and finally the tool itself detects an abnormality and stops. It transitions from the normal state to the abnormal stop state after the state where abnormality is detected. When an unscheduled tool stoppage occurs, parts replacement and maintenance may be required, resulting in a lot of downtime.

On the other hand, it is possible to minimize unscheduled downtime by detecting signs of abnormality early and taking measures before abnormal stoppage occurs. Early anomaly detection can minimize downtime by allowing replacement parts and maintenance to be scheduled in advance.

Our approach is:

- First, modelling steady state with machine learning
- Second, detecting anomaly symptoms by the deviation from steady state

3.2 Coolant system in lithography tool

In this paper, we studied failure prediction for a cooling system that cools a lithography tool drive unit. Figure 8 shows a schematic diagram of wafer stage and coolant system in lithography tool. Wafer stage is a drive unit and is composed of many sensors and actuators. The stage temperature is controlled by cooling water to control thermal deformation. When the cooling water absorbs the heat of the drive unit, the temperature of the cooling water itself changes and the flow rate of refrigerant is controlled by controlling the opening and closing of the valve to keep the cooling water temperature constant. In this cooling system, the valve that controls the flow rate sometimes fails due to wear or clogging due to solidification.

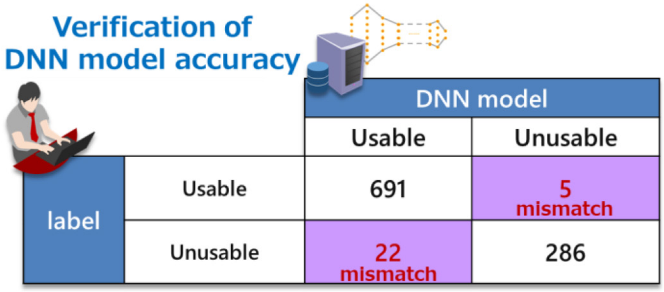

Figure 6. Confusion matrix for verification of transfer learning model.

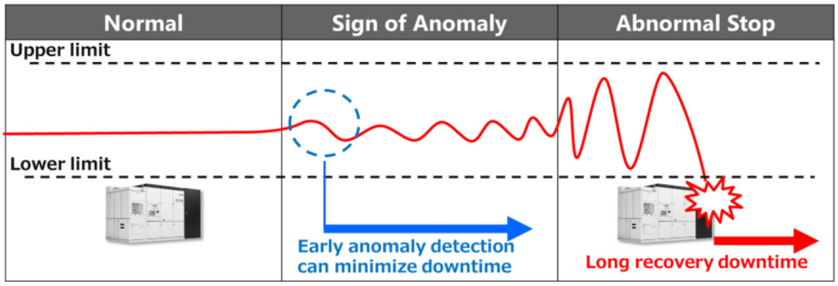

Figure 7. Lithography tool state.

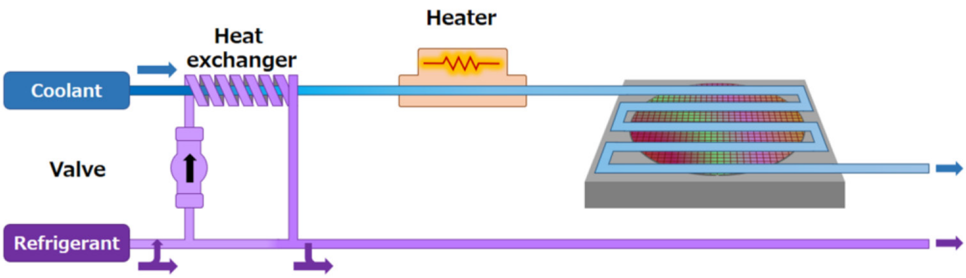

Figure 8. A schematic illustration of wafer stage and coolant system.

3.3 Machine learning model in steady state and monitoring

As illustrated in Figure 9, this system uses various temperature gauges and control value data to control the flow rate. Conventionally, the simple relationships of parameters that can be grasped by humans such monitoring Temperature-3 to Control-B and Temperature-1 to Control-A. Failure prediction through monitoring is desired. When a sign of failure can be detected, it is necessary to arrange a replacement part and detect the sign so that it can be replaced at the time of planned outage such as equipment maintenance. But there is a risk of sudden long-term downtime with single-parameter monitoring.

So our approach is to understand the detailed relationships with machine learning, which are learned by learning all 47 variables of temperature sensors and flow control values in the same system as features. We have studied failure prediction by grasping the degree of deviation from the steady state by applying Mahalanobis and Taguchi method (MT method).

Figure 10 illustrates the processing flow for model generation and deviation calculation.

We modeled 35 days of steady state data to detect anomalies (Figure 10 (a)). The latest state value is evaluated by dividing the time series data and creating several models, which is similar to bagging. The MT method is applied and the deviation is calculated for each model.

Specifically, a model is generated by the MT method from the data of the first 5 days, and the degree of deviation of this model and the latest value is quantified (Figure 10 (b)). Next, the degree of deviation is quantified in the same way with the data for the next 5 day period (Figure 10 (c)). This procedure is repeated to calculate the total deviation degree over 35 days (Figure 10 (d)).

Normal or abnormal is judged by comparing the calculated deviation with the threshold value calculated from the failure cases worldwide.

3.4 Anomaly detection case

Figure 11 illustrates the verification result. Using machine learning method, anomalies were detected 28 days earlier than conventional simple monitoring methods. Failure prediction in customer equipment has succeeded. Table 1 shows how long ago the machine learning model was able to detect anomalies with respect to conventional simple parameter monitoring in cases including the above case. We consider that the timing of abnormality detection differs depending on the case even with the same algorithm and threshold value because the failure mode is different or the characteristics of each equipment are different. For a more robust anomaly detection model, we believe that it is necessary to tune the generation period, weighting, and threshold of each model.

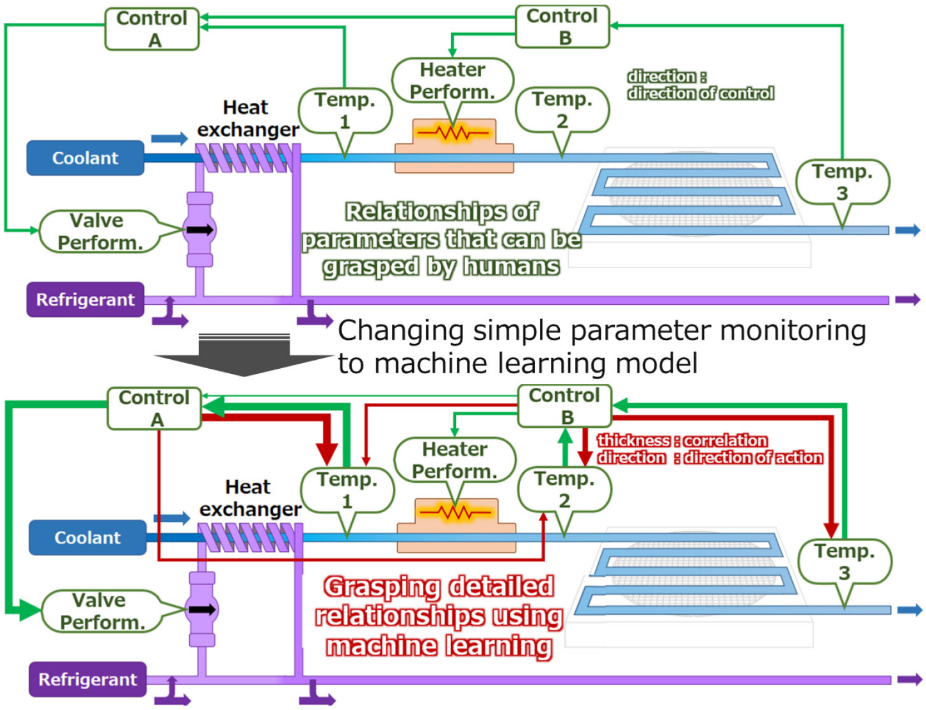

Figure 9. Simple parameter monitoring and machine learning model.

Table 1. All cases in coolant system abnormality occurrence.

Case	How long ago anomaly detected in machine learning ?
Case #1 (Figure 11)	28 days earlier
Case #2	22 days earlier
Case #3	16 days earlier
Case #4	2 days earlier

4. Results

We installed a data analytics server at our customer site for monitoring and developed various solutions to reduce unscheduled downtime such as trouble shooting and SOP notification, automatic recovery, and anomaly detection with machine learning.

Figure 12 illustrates the transition of unscheduled downtime rate (USD rate) for a specific customer. At the beginning of our project, USD rate was 2.3%. USD reduced year by year and finally reached 0.5% at the end of year 3. Image detection related USD reached almost 0% with measurements using deep learning. Anomaly detection of coolant system was detected once during the period. The lithography tool was restored without parts replacement.

5. Conclusion and Future Work

We have developed digitalization solutions utilizing most of the lithography tool log to improve uptime dramatically, and achieved to create innovative lithography tool value. Our digitalization solutions are highly effective in current pandemic.

The following items are future work in DL and ML techniques.

- Alignment improvement: robust image detection, multi-class classification by factor and automatic recovery for each factor, and visualization including object detection for explainable AI
- Overlay improvement: optimization of recipe parameters that learned the relationship between the prior distribution of recipe parameters and the posterior distribution of exposed pattern, or learned with reinforcement learning to improve the line width and overlay of the exposed pattern.
- Productivity improvement: less measurement using Virtual Metrology technology or sparse sampling and more precise anomaly detection using time series analysis method
- Service improvement: diagnostics and self-recovery with reinforcement learning

6. References

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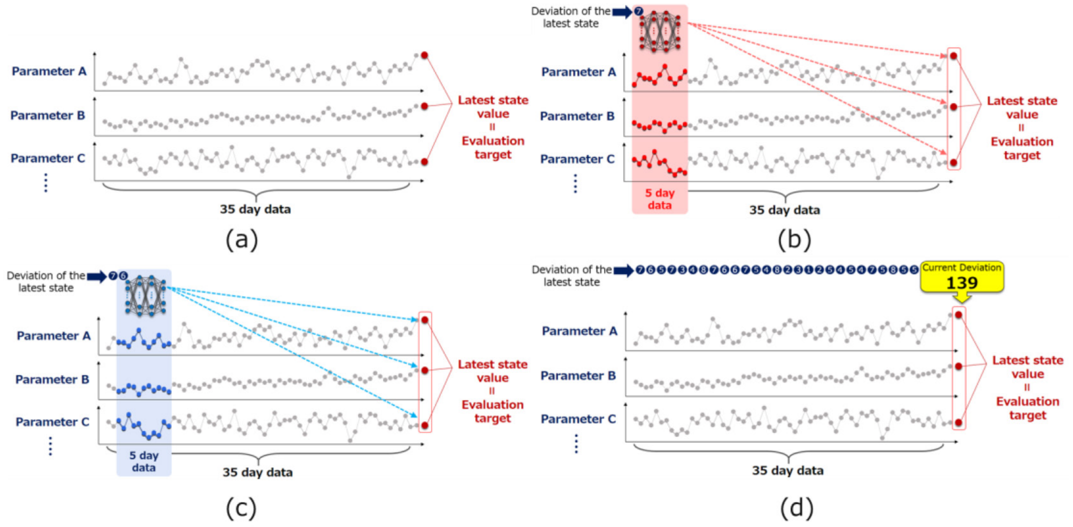

Figure 10. Processing flow for model generation and deviation calculation.

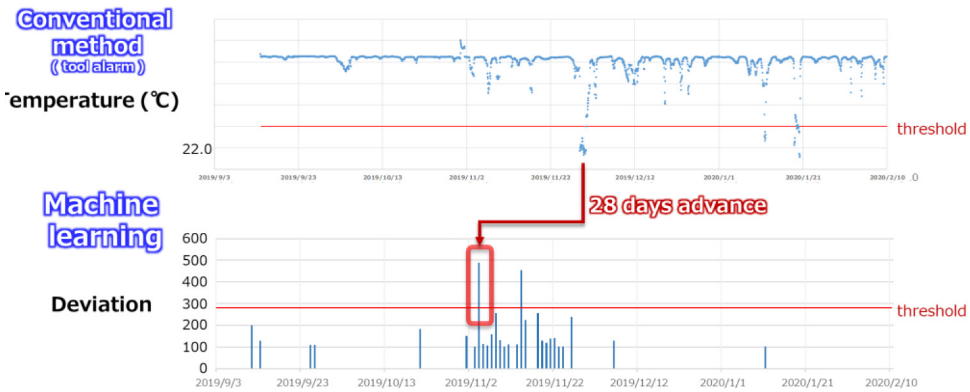

Figure 11. Verification result.

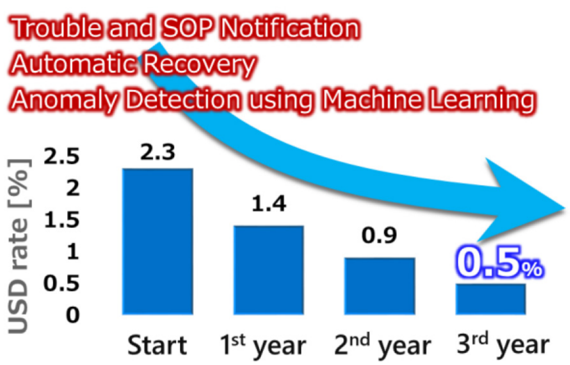

Figure 12. Transition of USD for a specific customer.

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Industry Briefs

Demystifying the Global Chip Shortage

Mark Harris, IEEE Spectrum

From PlayStations to Porsches, many consumer products have been hit by a chip shortage that began choking the global economy in 2020 and continues today. “We aren’t even close to being out of the woods,” U.S. Commerce Secretary Gina Raimondo tweeted last month. “The semiconductor supply chain is very fragile, and it’s going to remain that way until we can increase chip production.” Congress is poised to fund a US $52 billion silicon incentive package, as part of the America COMPETES Act, aiming to increase U.S. semiconductor manufacturing, while the European Union last week outlined their own €43 billion chip-shortage-ameliorating package.

https://spectrum.ieee.org/global-chip-shortage-charts

Intel Buys the Industry’s First Next-Gen Chipmaking Tool to Try to Reclaim Lead

Stephen Shankland, CNET

As part of Intel’s effort to reclaim processor manufacturing leadership by 2025, the company has ordered the first of a new generation of chipmaking machines from Dutch specialist ASML, the companies said Wednesday. The device, called the Twinscan EXE:5200, is scheduled to be delivered in 2024 for operations beginning in 2025.

https://www.cnet.com/tech/computing/intel-buys-the-industrys-first-next-gen-chipmaking-tool-to-try-to-reclaim-lead/#ftag=CAD590a51e

Luminaries See Growth Opportunities for Photomask Writers

Jan Willis, Semiconductor Engineering

Mikael Wahlsten of Mycronic describes that cost of ownership has been the focus for the development program of the new Mycronic SLX family of laser writers, which launched at the end of 2019. Mikael reports that 15 SLX units have been sold (as of September 28, 2021 and the total has increased to 21 as of February 2022). As reported in past eBeam Initiative surveys, more than 70% of the industry’s photomasks are written by laser writers.

https://semiengineering.com/luminaries-see-growth-opportunities-for-photomask-writers/

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Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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Overview and Request for Information
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Photomask Japan
26-28 April 2022
Digital Forum
www.photomask-japan.org

EMLC 2022
20-23 June
Leuven, Belgium
https://www.emlc-conference.com/

SPIE Photomask Technology + Extreme Ultraviolet Lithography
25-29 September 2022
Monterey, California, USA
www.spie.org/puv

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You are invited to submit events of interest for this calendar. Please send to lindad@spie.org.