OPTIMIZING ION MILLING PROCESS USING ADVANCED PROCESS CONTROL: INTEGRATING RUN-TO-RUN CONTROL AND FAULT DETECTION & CLASSIFICATION

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ABSTRACT

Ion milling process optimization has become critical for Air Bearing Surface (ABS) formation for Magnetic Recording Head Slider at WD-PHO. Traditional Ion Beam Etching (IBE) methods face challenges with process stability and defect formation, particularly affecting ABS slider performance. To address these challenges, an integrated Advanced Process Control (APC) system has been developed to enhance process control and defect mitigation.

This paper presents an APC system leveraging Run-to-Run (R2R) control and Fault Detection and Classification (FDC) algorithms for tool monitoring. The automated feedback mechanism demonstrates significant improvements in process control by minimizing variability and optimizing performance metrics. Implementation demonstrated a 40% reduction in process variation with direct impact on quality metrics and elimination of etch depth related scrapping.

The findings validate APC integration effectiveness for process optimization while maintaining yield targets. This approach provides a framework for precision manufacturing control in semiconductor fabrication processes.

1. 0 INTRODUCTION

Ion Beam Etching (IBE) is a critical process in advanced semiconductor fabrication that employs directional ion bombardment for precision material removal. The process occurs in a controlled vacuum environment where noble gas ions are accelerated toward the target surface. Material removal is achieved through kinetic energy transfer when the incident ion energy exceeds the surface binding energy threshold. Figure 1 illustrates ions accelerated towards the fixture holding the substrate.

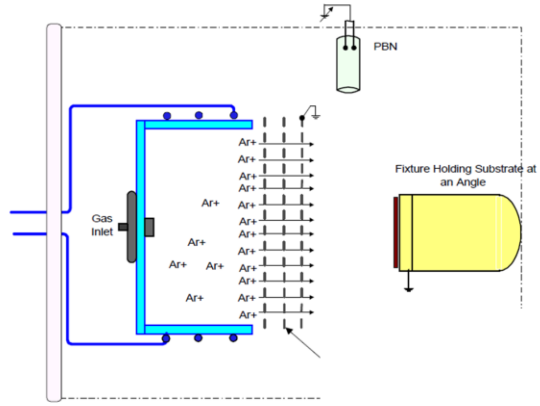

Fig. 1. Ionized Argon Gas (Ar+) accelerated toward the fixture holding the substrate.

This technique enables precise pattern transfer and critical dimension control in semiconductor device manufacturing. An illustration of this technique is shown on Figure 2, where a pattern on a substrate is being etched by ion beam. See also appendix B for the sample of slider's air bearing surface formation after etched.

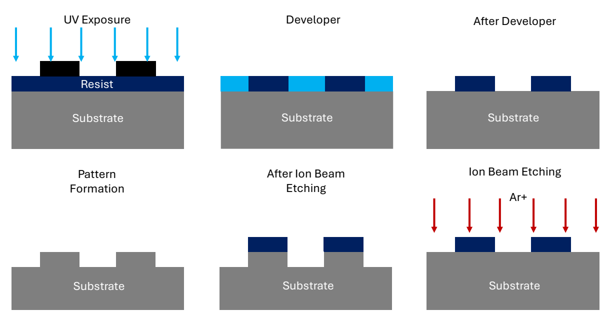

Fig. 2. Ion beam etching of substrate with photoresist to create pattern.

The IBE process parameters, including beam energy, incident angle, and gas chemistry, are optimized to achieve the desired etch characteristics while maintaining selectivity and minimizing redeposition effects. Process monitoring and endpoint detection systems ensure consistent material removal across the substrate surface[1].

1.1 Problem Statement

Despite IBE's established role in backend wafer fabrication, the process continues to face challenges including process variability, tool degradation, and defect formation. Specific to the air bearing surface (ABS) formation of HDD's magnetic head, also called sliders, these issues directly affect the slider performance metrics. To address these challenges, an integrated APC framework combining Run to Run (R2R) control and Fault Detection and Classification (FDC) algorithms offers a systematic approach for enhancing process stability and yield performance.

A significant limitation of current operations is the dependency on manual processing protocols. This workflow, as shown on Figure 3, requires technicians to calculate etch rates from previous batches and determine optimal process times using standardized templates. Following these calculations, parameters must be manually transferred to both documentation systems and tool interfaces. While error frequency remains relatively low, the repetitive nature of these tasks introduces potential for parameter mis-entry, which can result in process excursions and yield impact across multiple batches.

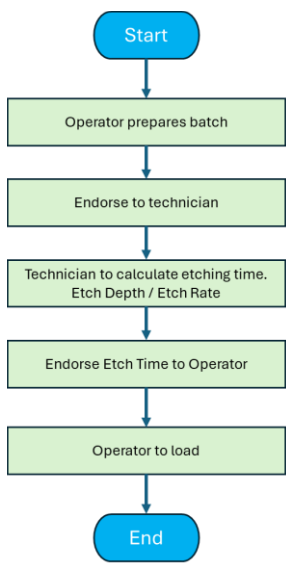

Fig. 3. illustrates role-based responsibilities between operator and technician. Operator to prepare the batch and load on IBE machine while the technician does the calculations.

1.2 Advanced Process Control (APC)

Advanced Process Control (APC) is a technology used in manufacturing semiconductor processes to optimize operations by automatically adjusting parameters based on real-time data. Figure 4 shows general APC Architecture.

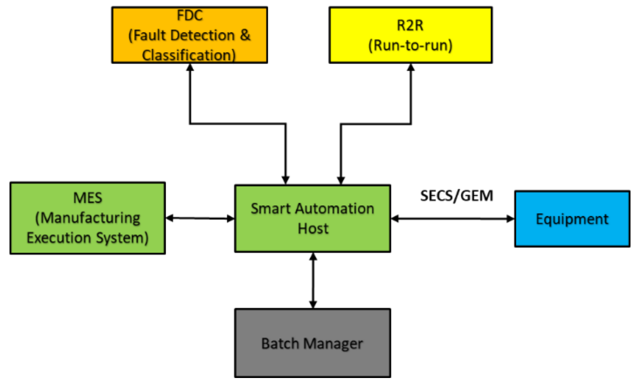

Fig. 4. Advanced Process Control (APC) Architecture

The architecture features a central Smart Automation Host that interface with five key components: (1) an FDC (2) R2R for process monitoring and control, (3) MES (Manufacturing Execution System) for production management, (4) Equipment (SECS/GEM) for machine communication, and a (5) Batch Manager for coordinating manufacturing operations[2].

2. 0 REVIEW OF RELATED WORK

Not Applicable.

3.0 METHODOLOGY

The methodology incorporates multi-parameter monitoring using FDC systems to track chamber conditions, gas flows, and pressure controls. Statistical process control techniques (R2R) are applied to maintain process stability and detect excursions. This approach enables precise control of material removal while maximizing throughput in high-volume manufacturing.

3.1 IBE APC System Architecture

A framework that has a capability for Automated Feedback Mechanism was developed. This Automated Feedback Mechanism has a closed-loop control that ensures continual optimization, reducing operator dependency. Figure 5 shows the framework of the IBE machine's APC.

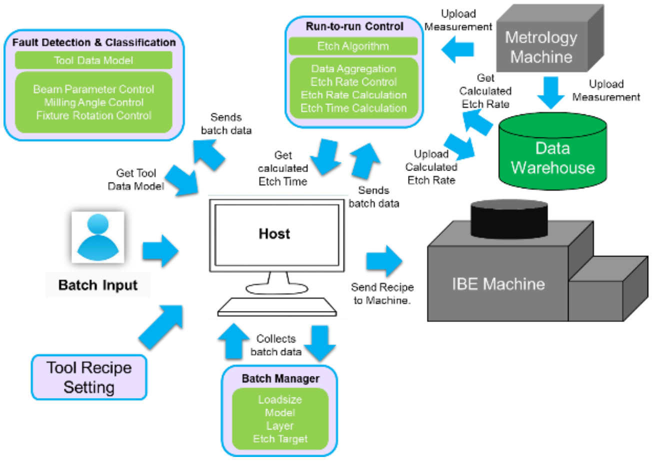

Fig. 5. IBE APC System Architecture

Typical of an APC architecture, the five key components are present in this automated feedback system. This integrated system enables a comprehensive manufacturing process control by connecting real-time fault detection with run-to-run adjustments while maintaining communication between production management systems and manufacturing equipment.

3.2 Smart Automation Host

An application that connects with the equipment via SECS/GEM (SEMI Equipment Communication Standard/Generic Equipment Model) was installed. This application instructs the equipment to process the materials and retrieve related information.

3.3 Batch Management

A sophisticated process queue management system was implemented to optimize the sequencing and processing of incoming workloads. This system facilitates the systematic organization of production units prior to their introduction into the manufacturing equipment. The architecture enables comprehensive tracking of critical process parameters that directly influence process control algorithms.

The system maintains detailed records of each production lot, including Batch Load Size, Model, Layer, and Etch Target, all of which plays a crucial role in Run-to-Run Control.

3.4 Run-to-run Control

An algorithm that is capable of data aggregation and process trend analysis was designed.

- Data Aggregation: involves collecting and analyzing process data to optimize the process.
- Process Trend Analysis: modifies the run-to-run control based on statistical trend of the process.

Combining Data Aggregation & Process Trend Analysis, provides Predictive Modeling capability for the R2R control. See figure 5 for the algorithm flow chart.

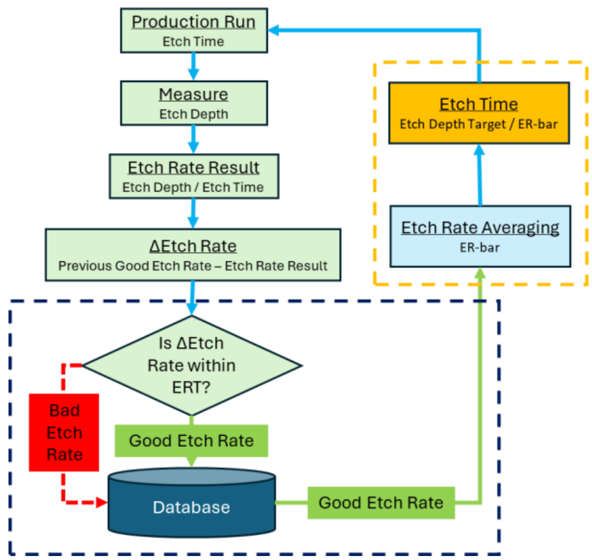

Fig. 6. Automated Feedback Mechanism. Dark Blue Dashed Box refers to Process Trend Analysis and Orange Dashed Box refers to Data Aggregation.

Fig. 6 illustrates an integrated Automated Feedback Mechanism as R2R control for etch rate stabilization. In each production cycle, etch depth is measured to calculate the etch rate result. This result shall be defined against the acceptable etch rate tolerance (ERT) limits, determined through historical trend analysis. If the Δetch rate falls within the ERT, it will be stored as Good Etch Rate, otherwise it will be stored as Bad Etch Rate.

For ion beam etching stability, etch rate is the main process control knob. Standard calculation of etch rate is provided below:

$$Etch\ Rate, A/s = \frac{Etch\ Depth\ (A)}{Etch\ Time\ (s)}$$

Where: Unit of measurement
A = Angstrom
s = Second

Etch Rate Tolerance (ERT) refers to the acceptable range of deviation from expected etch rate value. A moving range data with upper and lower control limits to distinguish bad etch rate and good etch rate. Figure 7 shows an example of moving range etch rate data.

- Bad Etch Rate is an anomalous or out-of-spec etch rate result with assignable cause.
- Good Etch Rate is an etch rate result within the normal process variation.

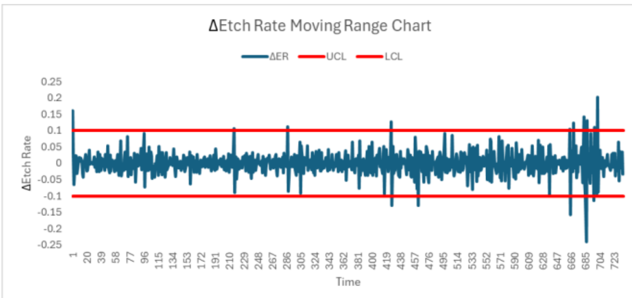

Fig. 7 Moving Range chart from ΔEtch Rate. UCL & LCL refers to the allowable limits of etch rate.

3.5 Fault Detection & Classification (FDC)

An anomaly detection algorithm that can mitigate process anomalies was also designed. This enhances the manufacturing efficiency by detecting deviations early and preventing defects.

The FDC depicts a systematic approach for semiconductor manufacturing tool monitoring and control, centered around the FDC: Tool Data Model. Figure 8 below illustrates the decision-making logic, data flow paths, and conditional branches that govern the manufacturing process control system.

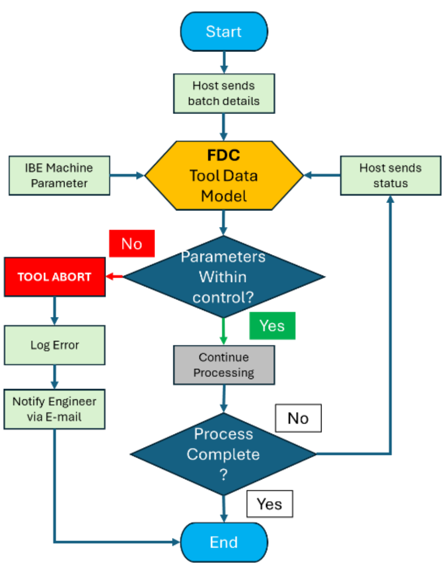

Fig. 8. FDC Workflow

Fig. 8 illustrates how the system monitors process parameters in real-time, makes decisions based on predefined control limits, and takes appropriate actions to either continue processing or abort operations when anomalies detected. In addition, it integrates automatic notification to engineers via e-mail which demonstrates the system's capability for rapid response to manufacturing issues. See appendix A for the reference e-mail alert.

The FDC Tool Data Model refers to the core component of the algorithm. This model-based approach allows for the specific parameter that needs to be controlled and provide an appropriate control limits based on historical trend analysis. See Figure 9 for the demonstration of control within the production run.

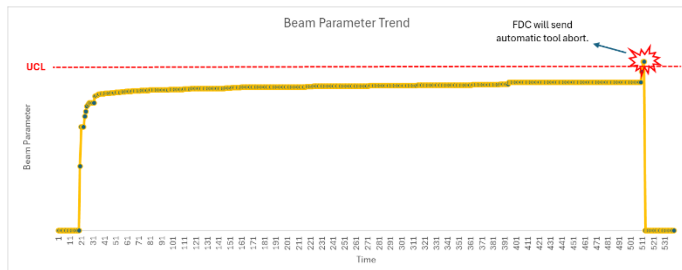

Fig. 9 Beam parameter trend chart showing trigger for tool abortion when there's an out-of-control.

3.6 Data Warehouse

A comprehensive data management system that serves as the foundation for advanced process control was implemented. This centralized repository aggregates manufacturing metrics from multiple sources including process time stamp, tool parameters, and quality measurements. The system architecture enables efficient storage and retrieval of critical manufacturing parameters such as process time stamp, product metrics, and timing measurements.

3.7 Testing and Validation

Lastly, a User Acceptance Test (UAT) to replicate real-world scenarios was conducted. These tests simulated how the System Architecture communicates, calculates, and adapts to different milling scenarios, ensuring smooth operation, accurate data processing, and effective fault detection. Table 1 summarized the test cases used by the tool users during the UAT.

Table 1. UAT Case Details

No.	Test Item	Case Details
1	User Account Login	User authentication both registered and unregistered accounts.
2	Batch Input	Batch Details validation from Batch Manager.
3	Host Connection	Host to Tool Application communication test.
4	Host Application Function	Test the command capability of host to tool.
5	FDC: Tool Alarm Detection	Test the FDC & host to identify tool alarm.
6	FDC: Tool Datalogging	Test the FDC Application if it downloads tool datalogs.
7	R2R: Etch Algorithm	Validate the result of etch rate & etching time calculation.

4.0 RESULTS AND DISCUSSION

This paper presents an Advanced Process Control designed to address the problem by integrating an Automated Feedback Mechanism, ensuring real-time adjustments, process stability, and optimized milling precision. Numerous IBE process Key Performance Indicators (KPI) improvements resulted from this project and are summarized in Table 2 below.

Table 2. Summary of KPI Improvement

No.	KPI	Details	POR	APC
1	Security Access	User Account Login	**X**	✓
2	Smart Automation Host	Automated Recipe Input	**Manual**	Automated
3	Tool Interdiction	Fault Detection	**X**	✓
4	Etch Algorithm	Recipe Selection	**Manual**	Automated
		Automated Etch Calculation	**Manual**	Automated
5	Data Traceability	Batch Manager	**X**	✓
6	Misprocess	Fault Detection	**X**	✓
		Automated Etch Calculation	**Manual**	Automated

4.1 Zero Scrapping: Out-of-Spec Etch Depth

The integrated system architecture (APC = R2R + FDC) enhanced overall yield by effectively eliminating etch depth related scrapping, as shown on Figure 10. The full implementation of the APC was realized starting year 2024.

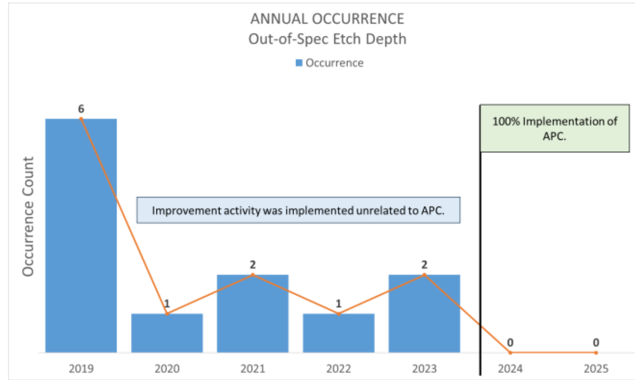

Fig. 10 illustrates annual occurrence of etch depth related scrapping.

4.2 Optimized Performance and Resource Utilization

As shown on Figure 11, occurrence of scrapping due to misprocess (Man/Operator) was eliminated. The chart highlights the effectiveness of Run-to-run (R2R) control algorithm, which successfully automates recipe adjustments, removing the need for manual input. This enables the operator to dedicate time to other essential tasks.

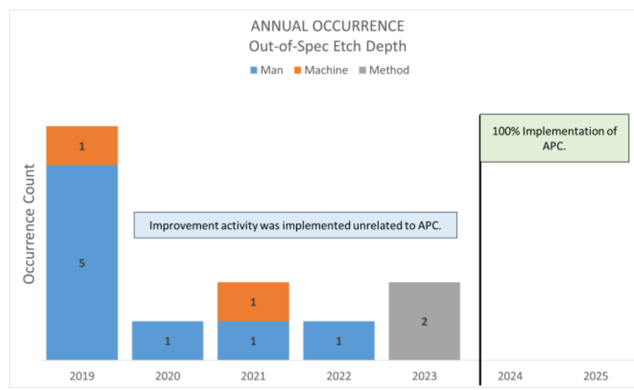

Fig. 11. Annual Occurrence Summary by Root cause (5M1E)

4.3 Process Variability Reduction

Another key variable that has shown the effectivity of the run-to-run control and fault detection algorithm is sigma. As shown in Figure 12 below, the algorithm was able to reduce the variation by approximately 40%. This reduction contributed on enhancing the product's overall performance.

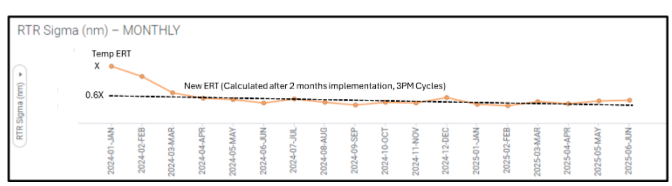

Fig. 12. Monthly trend of run-to-run Sigma

5.0 CONCLUSION

By transitioning from human-dependent process to a fully Advanced Process Control system, process variability was significantly reduced, leading to improved product performance and the elimination of etch depth related scrapping. This enhancement directly contributed to increased overall yield.

In conclusion, Advanced Process Control (APC) serves as a highly efficient solution for optimizing process stability, performance, and yield in precision manufacturing.

6.0 RECOMMENDATIONS

The findings in this technical paper highlights the critical role of the algorithm in the system architecture. To further enhance its effectiveness, a deeper analysis of historical process data is recommended. Leveraging these insights can refine the algorithm, improving its accuracy and adaptability to varying operational conditions.

However, its optimization remains constrained within the current process setup. To fully explore its potential, adjustments to the machine process recipe should be considered. Implementing a Design of Experiments (DOE) approach will provide a structured methodology for identifying optimal parameter configurations, ensuring systematic improvements and enhanced process efficiency.

7.0 ACKNOWLEDGMENT

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8.0 REFERENCES

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10.0 APPENDIX

Appendix A. **FDC - Auto-Email Alerts**. An e-mail alert is sent to the sustenance team enabling rapid response. The e-mail alert contains general information from the affected batch.

ATTENTION!!! - TESTING!

Beam Voltage is at stepnumber 3. Please check.

Batch ID: 171297

Recipe:

This is a system generated message, please do not reply on this e-mail. Thank you.

HNY - Fault Alert and Detection

Appendix B. **Air Bearing Surface Formation**. An ABS formation for Magnetic Recording Head Slider. The ABS shows the pattern after being processed to ion milling machine[3]