HOST-CONTROLLED LITHOGRAPHY: AN INTEGRATED SYSTEM FOR AUTO-RECIPE MANAGEMENT AND HOST-GUIDED EXPOSURE INITIATION

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ABSTRACT

Manufacturing automation represents a critical enabler for Western Digital's (WD) Industry 4.0 roadmap, particularly in lithography operations where manual recipe management introduces significant risk. Current manual processes for recipe selection and mask alignment verification create exposure to yield excursions, cycle time delays, and quality escapes. This paper presents an integrated host-controlled lithography system that implements automated recipe validation, real-time fault detection and exposure initiation control through Machine Execution System (MES) integration. The system architecture employs a structured file-based communication protocol that facilitates bidirectional data exchange between the host environment and the UV exposure tool.

Implementation results demonstrate significant improvements in key metrics including zero quality escapes from recipe mismatch and 8.1% throughput improvement. These outcomes contributed to improved process repeatability during slider air bearing surface (ABS) formation, thereby supporting consistent product performance. This host-controlled system serves as a blueprint for the elimination of manual intervention risks in lithography operations and advances WD's Industry 4.0 transformation.

1. 0 INTRODUCTION

The magnetic head slider constitutes a fundamental component in hard disk drive (HDD) architecture, facilitating reliable data read and write operations. Within the slider fabrication process, the air bearing surface (ABS) design and manufacturing precision are critical determinants of overall drive performance. Typical ABS features include a step or raised sections at the rail side and along the leading and trailing edges, and a center portion that is normally recessed[1].

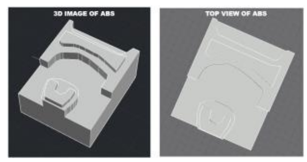

Fig. 1. Typical ABS Images (L) 3D Image (R) Top view

These recessed and raised step surfaces shown in Figure 1 are designed to modulate air pressure to help the magnetic head glide above the surface of the media or more popularly known as disk inside the HDD. The total pressure difference created between the recessed and raised step surfaces leads to a vertical force balanced by bending a flexural element in the support arm while the flying height and attitude are controlled by the equilibrium between the aerodynamic and bending forces[2]. Flying Height refers to the physical gap between the slider and the disk as the slider on a gimbal assembly flies over a rotating disk. For a specific slider design, fly height and shock stiffness are determined by the ABS' geometry[1].

1.1 ABS Forming Process

The microscale ABS features of a magnetic head is formed from iterations of photolithography and ion milling process as illustrated in Figure 2.

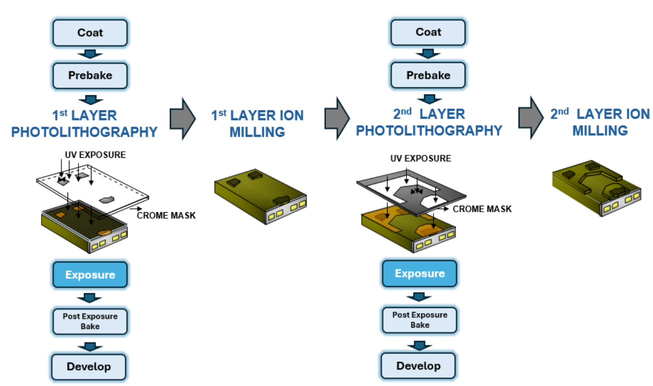

Fig. 2. ABS Forming Process[1]

The process begins with photoresist coating on the substrate, followed by UV light exposure through a precision chrome mask. This exposure step defines the pattern by selectively altering the solubility of the resist. A development process is then used to remove the exposed or unexposed regions of the resist, depending on whether a positive or negative resist is used. The patterned resist functions as a sacrificial mask during subsequent ion milling process, wherein ion bombardment physically removes material from exposed substrate areas to create the specified step heights and recessed depths[3].

For multi-level ABS designs characteristic of advanced products, the process is iterated with different masks and etch parameters to construct complex three-dimensional topography required for optimal flying characteristics. Each iteration necessitates precise alignment to previous layers, with registration tolerances in the sub-micron range.

Upon completion of the desired lithography and milling process iterations, in-process metrology or post-process inspection is typically performed to verify critical dimensions, line widths, etch depths, and surface quality, ensuring compliance with design specifications.

1.2. The UV Exposure in ABS Forming Process

Ultraviolet exposure represents a critical control point in the ABS formation process sequence. During this operation, the product-specific ABS pattern encoded in the photomask[3] is transferred to the wafer surface with precision.

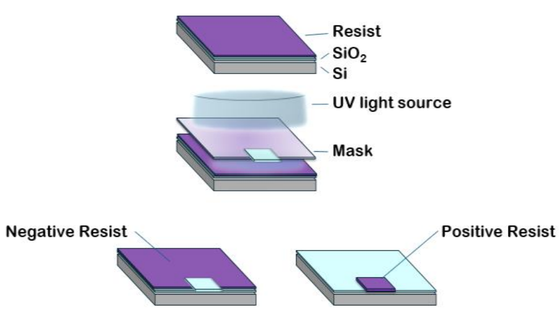

Fig. 3. UV Exposure Step in ABS Forming Process

In UV Exposure Process shown in Figure 3, a UV light source is directed through a photomask, which contains specific patterns formed by transparent and opaque regions. These regions define the locations on the photoresist where the UV light can penetrate.

- Positive Photoresist: The regions exposed to UV light become more soluble in the developer solution.
- Negative Photoresist: The exposed regions become cross-linked and less soluble, while unexposed areas are removed during development.

The result of this exposure is a latent image in the resist, corresponding to the photomask pattern.

1.3. Problem Statement

The complete fabrication of a slider's air bearing surface involves the use of multiple photomasks, with each mask defining specific features of a structural layer. Given that each HDD product requires a uniquely tailored ABS design to meet specific mechanical performance criteria, precise alignment between the photomasks and corresponding product specifications is critical to ensuring dimensional accuracy and functional integrity during ABS formation.

However, one recurring and costly issue is the misalignment between reticle selection and process parameters—commonly referred to as "wrong mask exposure." These errors can lead to rowbar scrapping, yield loss, production delays, and increased operational costs.

Currently, the UV exposure tool input validation in Western Digital Philippines' Head Operation (WD-PHO)—such as matching reticle ID, product type, and process recipe—relies on manual verification or tool-side checks that are susceptible to human error or configuration mismatches. The absence of a centralized control mechanism for pre-exposure validation has proven to be a major weakness in maintaining data integrity and process reliability. Figure 4 illustrates the current Exposure Tool Recipe Management System of PHO.

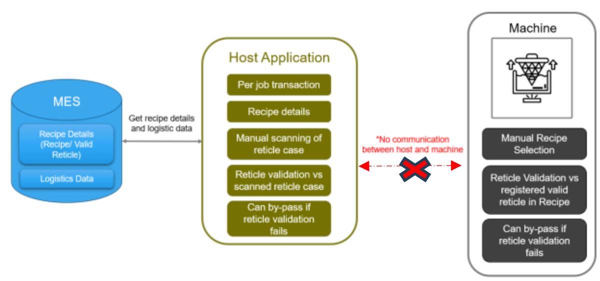

Fig. 4. Current UV Exposure Tool Recipe Management

The host application operates without batch information, requiring per-job transactions via manual traveler scanning. Reticle validation depends on manual reticle case scanning due to absence of host-machine communication, creating potential for incorrect case scanning. More so, validation may be bypassed despite failures. While tool recipes contain registered valid reticle information, manual recipe selection allows exposure process to proceed despite reticle-recipe mismatch.

This paper addresses the problem by introducing a host-controlled lithography framework that integrates (1) Batch information uploaded via a centralized Batch Manager, (2) Automated cross-verification of Reticle ID, Recipe, and Product details for fault detection and (3) Host-driven exposure initiation based on successful validation of inputs. The system integration is facilitated through the implementation of a file-based communication protocol that establishes a structured interface between the host system and the machine, in this case, the UV Exposure tool.

2. 0 REVIEW OF RELATED WORK

Refer to 1.0 Introduction.

3.0 METHODOLOGY

To shift the control and validation logic of PHO's lithography process to host level, The Host Controlled Lithography Framework shown in Figure 5 was executed by the authors.

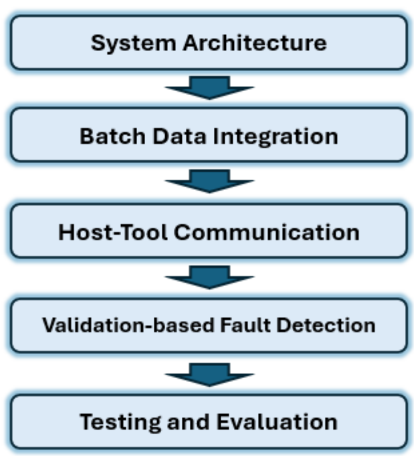

Fig. 5. Host Controlled Lithography Framework

3.1. System Architecture

The project commenced with the development of a host-controlled lithography system architecture, as illustrated in Figure 6.

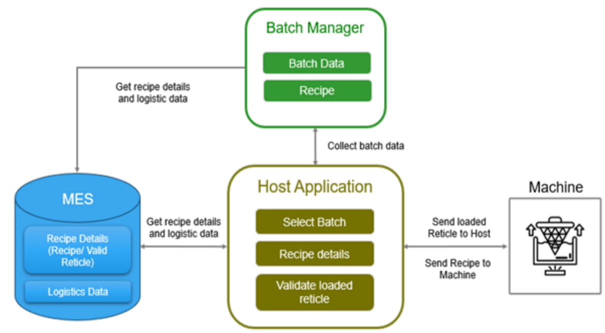

Fig. 6. System Architecture for Host-Controlled Lithography

The Host-controlled system consists of a Batch Manager and a Host Application, which are connected to the MES and the machine that performs the online process. The Batch Manager gathers all job information and recipe details, including the valid reticle, from the MES. When the operator then loads the reticle into the machine, the machine sends the reticle ID to the Host Application via file communication. The batch data is then loaded into the Host Application, where the system matches the batch recipe's valid reticle against the actual reticle. If the validation fails, the process will not proceed and cannot be bypassed. If it passes, the Host Application will send the batch recipe to the tool, and the exposure process will be initiated.

3.2. Batch Data Integration

Following the establishment of the system architecture, an automated batch upload module was implemented through the Batch Manager to facilitate the pre-registration of anticipated lithography inputs. The Batch Manager oversees the data that will be processed in Host application. It validates each job if allowed to proceed by checking job operation and recipe. The Batch Manager gathers all the details for the batch (e.g. Product type, format, mapping of good units, etc.) from the MES and then matches these with the stored recipe in the tool in preparation for processing. The Batch Manager also generates a unique Batch ID for the grouping of the units for processing. This grouping ensures that there will be a representative data coming from any of the units of the batch for the critical parameters' measurement ensuring that the batch passes the criteria. Figure 7 below shows the batch information collected in the Batch Manager.

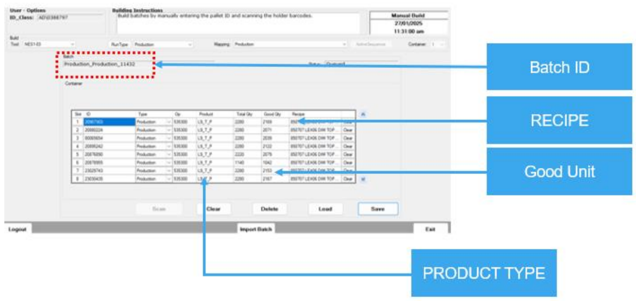

Fig. 7. Sample of Batch Manager

3.3. Host-Tool Communication Protocol

To establish the desired communication protocol, a robust and secure communication interface between the machine and the host system was developed. In collaboration with the equipment manufacturer, a file-based communication architecture was implemented which enables the exposure machine to transmit control signals to the host environment via structured file exchanges.

This methodology necessitates the development of multiple specialized file formats, each representing distinct communication protocols within the overall system architecture. The implementation of these differentiated file structures enables comprehensive command and control capabilities while maintaining system integrity and operational security.

3.3.1. The Status File (SV)

This status file allows continuous updates so the host application can verify ongoing connectivity to the machine periodically. Figure 8 below shows the Status File Communication Workflow.

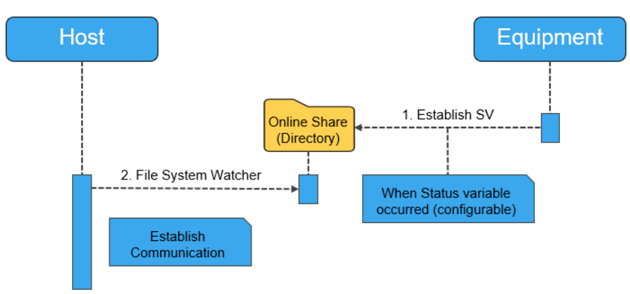

Fig. 8. Status file communication Workflow

3.3.2. The Event File (EV)

The event file allows the host application to identify all the events occurring on the machine side which includes the following events:

1. Reticle Align Event: Triggered when reticle alignment is performed, including the scanning of the reticle ID, which will be sent to the host.
2. Start Event: Indicates the actual start of a job, prompting the host to initiate a MES start transaction.
3. Align Event: Captures alignment data for each row/bar alignment, which the host will upload to the parametric database.
4. Expose Event: Captures exposure data for each row exposure, which the host will upload to the parametric database.
5. End Event: Indicates the completion of the job, prompting the host to perform a MES end transaction.

Refer to Figure 9 for the details of the Event File Communication Workflow.

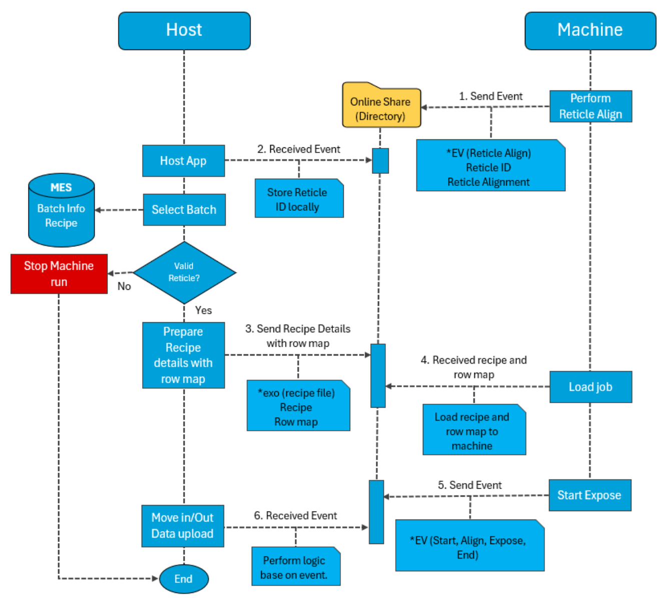

Fig. 9. Event file communication Workflow

3.3.3. The Alarm File (AL)

The Alarm file provide alarm event notifications to the host, including details of which specific alarm occurred on the machine, so the host can display the actual alarm message. Figure 10 below shows the details of Alarm File Communication Workflow.

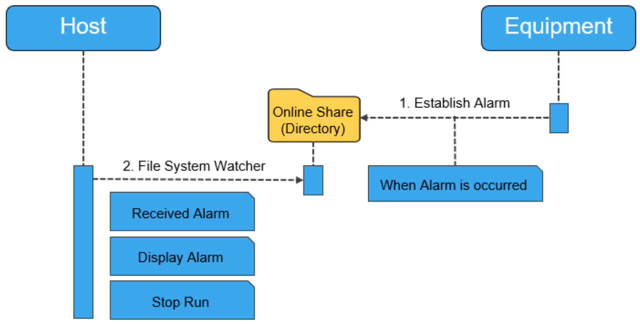

Fig. 10. Alarm file communication Workflow

With the availability of these file communication protocols, the host and the tool have unique identifiers in the system to ensure that the set of instructions sent by the host are directed to the correct machine and vice versa.

3.4. Validation-based Fault Detection

A logic to compare tool-loaded reticle data with the batch-registered values was built. This will ensure that any check item that does not match with the requirement will automatically place the affected jobs in hold state awaiting confirmation of the error by the operator. A warning will be generated and flashed on the machine screen to capture the operator's attention. The exposure will automatically be inhibited to proceed in this case. Similarly, appropriate data logging and notification will be executed.

Figure 11 illustrates the Validation-based Fault Detection Workflow while Figure 12 shows a sample error message once a certain validation criterion is not met.

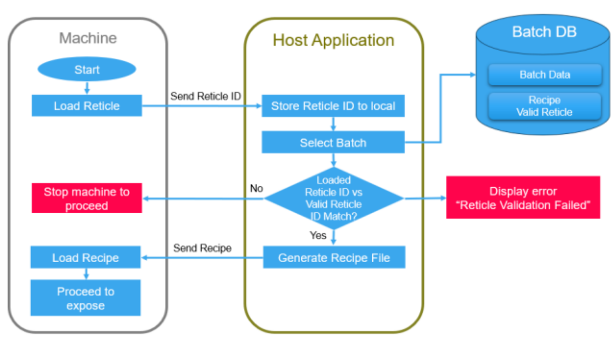

Fig. 11. Validation-based Fault Detection Workflow

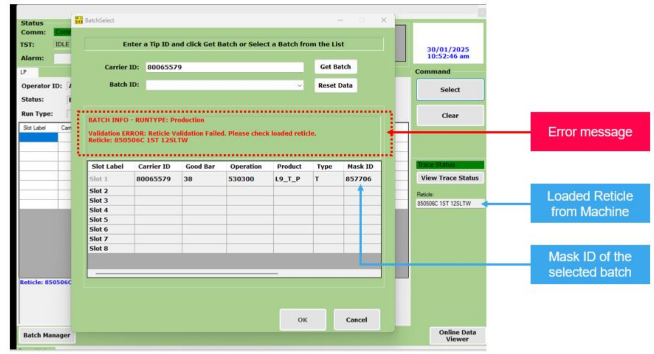

Fig. 12. Sample error message

3.5. Testing and Evaluation

Real-world production scenarios are simulated including both correct and incorrect input combinations thru conduct of User Acceptance Test (UAT). Actual tool and systems users (Production Operator & Process Engineer) performed the test according to a set of test scenarios provided in Table 1.

Table1. Test Case Details

Item	Test Item	Case Details
1	Login Authentication	Host application will authenticate user log in
2	Communication	Host application and exposure tool communication test
3	Tool Alarm	Test when the tool send alarm to host
4	TST Status Check	Test the connection with TST
5	Mismatched tool ID vs Host Entity	Check if the tool ID setting is correct.
6	Batch Select (Without Reticle Align)	Selection of batch without reticle align event performed
7	Reticle Align	Host application acknowledge reticle align event
8	Batch Select	Batch and lot validations in Batch Selection
9	Reticle ID Validation	Validate if reticle ID stored in tool is correct based on the process details of the Job
10	Complete Transaction	This test case is a complete transaction test. Outputs are (KIV Data upload, Auto moveout carrier, auto validation, exposure initiation)

4.0 RESULTS AND DISCUSSION

This paper successfully addressed wrong mask exposure problem by introducing a host-controlled framework that integrates a batch manager, an automated validation and a host driven exposure system. The system upgrades introduced by this integrated system is summarized in Table 2 below.

Table 2. Host-Controlled Lithography Features

Item	Features	Details	Old System	Host-Controlled
1	Access security	User login verification	X	O
2	Host to Tool Communication	Recipe selection	Manual	Automated
		Reticle verification	Manual	Automated
		Host-UV Tool Communication Protocol	X	O (File-Based)
3	Misprocess prevention	Recipe selection	Manual	Automated
		Fault Detection	X	O
4	Logistic data traceability	Batch traceability (e.g. Operation, Tool ID, etc.)	X	O

x = none, O = available

These features were tested and validated by the tool users thru the conduct of the UAT defined test conditions listed in Table 1. The application of these enhanced features led to ABS formation process' KPI improvements as summarized in Table 3.

Table 3. Summary of KPI Improvement

Item	KPI	Details	Old System	Host-Controlled
1	Exposure Process Throughput	No of Jobs/week	X	1.08X
2	Cost of Quality Escapes	Wrong Mask	1x / 2 years	None

4.1. Zero Occurrence of Wrong Reticle Exposures

The integration of batch manager and the host-controlled exposure initiation fool proofed the exposure process and led to the complete elimination of incorrect reticle-related process errors through automated input validation. Although previous instances of wrong mask usage are detectable in subsequent processes, these adversely impacted productivity due to tool downtime for failure analysis, increased process rework, and delays in product shipment. Over the five months implementation of this new system, there are zero occurrences of wrong mask.

4.2. Higher Output, Greater Consistency, Sustained Performance

The implementation of the Host-Controlled Lithography resulted to a 1.08x times improvement in weekly output volume. This significant increase demonstrates enhanced throughput capacity achieved through the transition from manual to automated process. This increase per week shown in Figure 13 represents a significant operational efficiency gain that can be directly attributed to the automation implementation. In addition, the host-controlled process shows more stable output with less week-to-week variation.

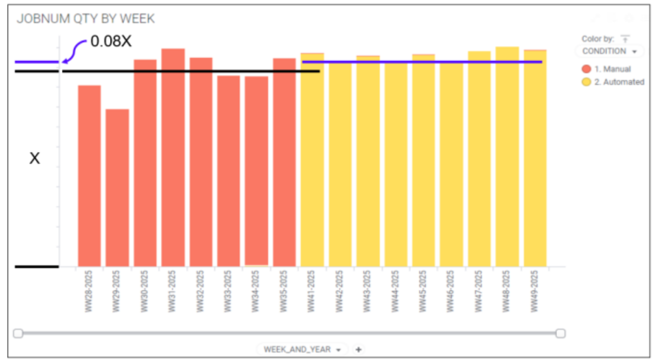

Fig. 13. Output Job Qty per Week of photolithography tool.

4.3. Other Improvements from the Host-Controlled Lithography

- Host-mediated control ensures stricter adherence to process parameters and sequencing.
- All validation and control actions logged at the host level provide better visibility for root cause analysis and process audits.

All the improvements mentioned resulted to a more stable and repeatable slider ABS formation, thereby enhancing overall product performance stability.

5.0 CONCLUSION

By shifting control and validation logic to the host level, this system was able to eliminate human-dependent checks, ensure correct reticle usage, and prevent misprocessing. This automation solution also enhances traceability, enforces process discipline, and contributes to a more intelligent and error-proofed photolithography process used for slider's air bearing surface formation, ensuring consisted and repeatable product performance.

The transition to automation has also resulted to an 8.1% higher throughput and more predictable processing volumes, which would likely translate to better resource planning and operational efficiency.

6.0 RECOMMENDATIONS

Control and validation logic at host level is one step to introduce and integrate APC (Advanced Process Control) in Lithography process. Migration to the next level thru APC will involve the use of several techniques, mathematical methodologies, and statistical models to optimize process control by controlling several significant variables of the process. Thus, it is highly recommended to adopt APC in Lithography for WD's further advancement in Industry 4.0.

7.0 ACKNOWLEDGMENT

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10.0 APPENDIX

Not Applicable