TECHNICAL GUIDE

Advanced MES Capabilities for Semiconductor Front-End Manufacturing

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Introduction

Semiconductor manufacturers are facing tremendous challenges: rising customer demand, rapidly increasing product complexity and expanding product portfolios are all creating formidable operational hurdles. On top of that there is a pressing need to increase the speed of innovating and ramping up new products and processes.

It is well known that semiconductor chip production is the most capital and R&D intensive manufacturing process in the world. Every semiconductor front-end wafer manufacturing facility (fab) represents billions of dollars of investment in facilities, equipment and personnel. Semiconductor fabs operate around the clock in strictly controlled clean room environments with tightly controlled processes of extreme precision and accuracy. A single manufactured product may consist of tens of layers and require hundreds of manufacturing process steps across a variety of sophisticated tools and machines.

Manufacturers are realizing that to increase speed, improve process reliability and get the best return on their investments they can no longer rely on the way they worked in the past. They need a modern Manufacturing Execution System (MES) that can keep pace with the evolving demands of the advanced capabilities needed for process modeling and execution.

The following sections will explore the manufacturing scenarios, challenges and the critical advanced capabilities that must be supported by a modern semiconductor front-end MES:

Master Data Management

The Challenge

For a single product, manufacturers must manage the process flow, recipes, recipe programs and recipe parameters as well as reticles, BOMs, data collections, specification limits and sampling strategies. Maintainability and Change Control are two key elements of Master Data Management.

Maintainability requires that different elements can be re-used as much as needed with good visibility about the complete process of record (PoR) for a product or lot. In semiconductor front-end manufacturing, there are common sub-flows that are repeated for every layer, with small changes (e.g.: to the recipe, to the reticle or to the limits) as shown in Figure 1. Having the capability to re-use entire sub-flow blocks is essential for good master data management. System re-usability reduces the number of master data elements and is typically achieved with a flexible context matching mechanism.

Change control must enforce that new revisions and new versions follow a well-defined approval process with easy revision of each master data element assigned to a particular object, such as the revision of the flow assigned to a product and the revision of a product assigned to a lot. A common issue is that some execution relevant master data is maintained in separate enterprise systems, such as the Product Lifecycle Management (PLM) or Enterprise Resource Planning (ERP) systems, making it important to integrate with these systems to reduce effort, time, and opportunities for errors.

The Solution

The MES must deliver change management and versioning capabilities to support the required level of change control. Furthermore, in order to provide flexibility while improving the re-usability of common elements (e.g.: Data Collections and Recipes), the linkage between a product or lot, and the elements to be used at a particular process step, must be linked using a flexible context resolution mechanism and not hard linked. In addition, to support modularity and maintainability, the MES must provide a mechanism to re-use complete flow blocks multiple times when defining a new flow, while being able to set the appropriate context (e.g.: layer number) so that the different process elements can be resolved correctly.

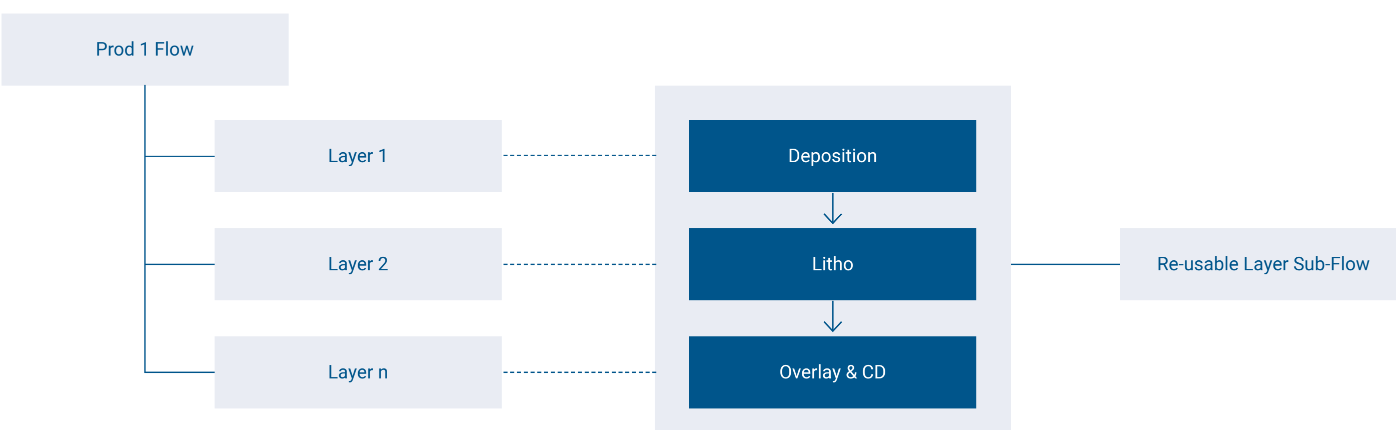


Fig. 1 Repeated re-usable Sub-Flows

Experiments Management

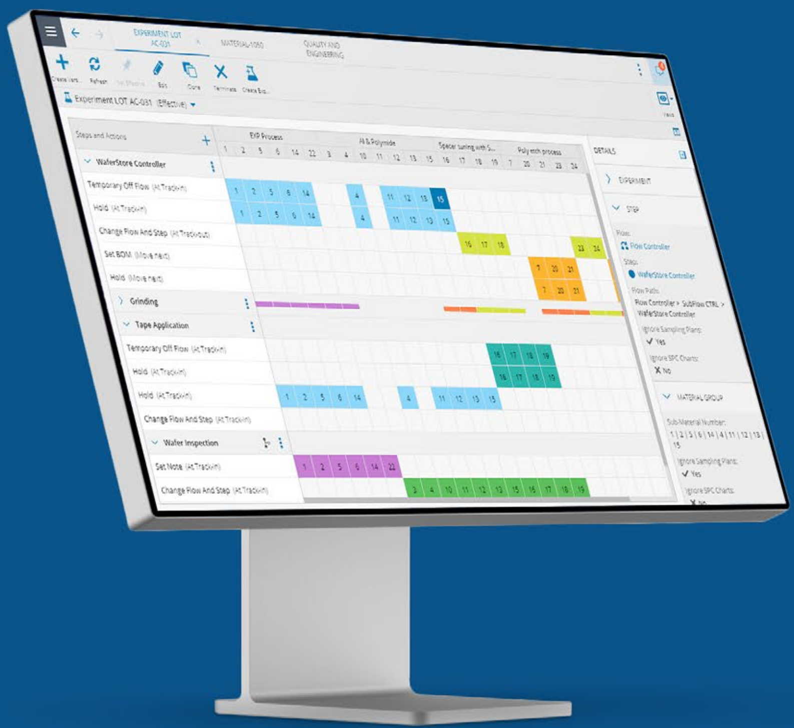
The Challenge

Experiments are used to develop or improve products, processes (e.g. chamber matching), equipment, and materials. Experiments consists of two parts: the design of the experiment (DoE) and the execution of the experiment. An experiment represents one or more variations to a standard process flow, designated as the Process of Record (PoR). Ideally, the design and the execution should take place in the same system to provide a seamless data flow and transparent experiment execution when the experiment takes place along mass production lots.

Because wafers are tracked individually in a semiconductor front-end, multiple process variations in a single lot can be combined in a single experiment, as shown in Figure 2. As part of the experiment, wafers will be split and merged at well-defined points, and each group of wafers will be subject to its own particular set of variations at a given process step. At the end of the experiment, the full history and data collected for each wafer should be available to analyze the effects of different variations, so that conclusions can be reached.

The Solution

The MES must provide an integrated Experiment Designer that supports the concept of experiment wafer groups and also a rich set of process variations that reference any existing MES process element (e.g.: Recipe, Data Collection, Process Flow). The Experiment Designer must also support splits and merges for the different wafer groups at different process steps. A fully integrated Experiment Designer makes it easy to create and execute experiments seamlessly and transparently, together with all other production lots. The MES must collect all history and traceability data for each wafer to evaluate the results of the experiment.



	Wafer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Group A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Group B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Group C	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Step	Action																									
Exposure layer 1	1. Physical Split For Step	1	2	3	4		6		8																	
	2. Override Mask - use Mask M04L2	1	2	3	4		6		8																	
	"No Action - use POR"					5		7		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CD 1	1. Physical Split For Step										10	11	12	13	14	15	16	17	18	19						
	2. Override Recipe - use Recipe R5200A										10	11	12	13	14	15	16	17	18	19						
	3. Override Data Collection - use DCEV24B										10	11	12	13	14	15	16	17	18	19						
	"No Action - use POR"	1	2	3	4	5	6	7	8	9											20	21	22	23	24	25
Stripping 1	1. Permanent Split					5		7	8	9											20	21	22	23	24	25
	2. Move to Flow Exp10V2 Step Oxidation 4					5		7	8	9											20	21	22	23	24	25
	1. Temporary Split/ Future Merge at Oxidation 3										10	11														
	2. Move to Flow Exp10V2 Step Overlay 4										10	11														
	"No Action - use POR"	1	2	3	4	5	6	7	8	9			12	13	14	15	16	17	18	19	20	21	22	23	24	25
Oxidation 3	1. Physical Split For Step	1	2	3	4		6		8																	
	2. Hold (reason = Experiment)	1	2	3	4		6		8																	
	"No Action - use POR"					5		7		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Fig. 2 Example of an experiment definition

Recipe Management

The Challenge

A recipe is a critical process element that consists of the recipe program, recipe parameters and sub-recipes. Some recipe programs are complex and require special recipe editors or software development kits (SDK). It's important to ensure that approved recipes that are uploaded to the appropriate equipment are not changed in any way. Recipe parameters can be static or dynamic and are a key enabler for re-using recipes. For increased modularity and re-usability, recipes can include sub-recipes that receive parameter values as input from the parent recipes.

A critical aspect of a recipe management is the capability to verify that the right recipe is used for a specific material, product, process flow or process step at the correct equipment. The recipe resolution process is responsible for the calculation of all the recipe parameters that will be used as part of an equipment run. These parameters can be static or dynamic, such as in the case of calculated Run-to-Run values (see section later in this document). For traceability and process improvement purposes, the specific recipe version and individual recipe parameter values that were used for each material process must be captured. The relationship between the recipe definitions and the recipe instances is shown in Figure 3.

The Solution

The MES must provide an centralized Recipe Management System (RMS) that allows recipes to be uploaded to and downloaded from equipment using equipment integration. The MES must also provide a flexible context resolution to resolve and verify the recipe to be used for a particular lot at a particular piece of equipment in a particular process step. To ensure complete traceability and support process improvement, the MES must capture the exact recipe version as well as the set of parameter values used for each job. For high-automation purposes, it must be possible to upload or select the approved recipe at the equipment via integration. For process integrity purposes, the system must ensure that the recipe to be used has not been modified.

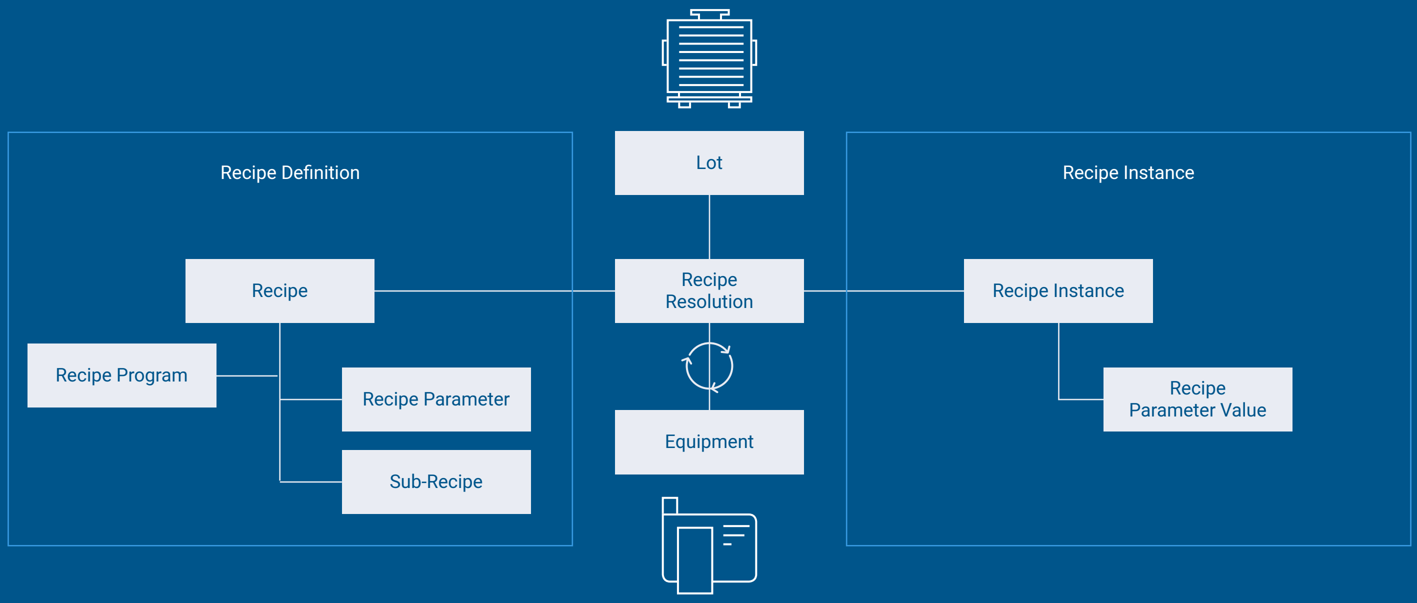


Fig. 3 Recipe Definitions and Recipe Instances

Run-to-Run

The Challenge

Front-end semiconductor manufacturing requires a high degree of control that is provided by feedforward and feedback control loops as shown in Figure 4. These control loops provide information to fine-tune and adjust recipe parameters to improve the performance and yield of a lot, for example, to adjust the CMP polish times according to thickness measurements.

At the core of Run-to-Run is a controller that consists of a process specific model used to calculate recipe parameter values based on feedforward (or feedback) information. The model can be constantly refined using feedback from the actual observed effects when the model is applied. The Run-to-Run controller should be called explicitly by a Recipe Management system that also supplies all the necessary context to calculate the required dynamic recipe parameter values.

The Solution

The MES system must be able to capture all the lot, wafer and process information required for both feedforward and feedback control. As part of an integrated Recipe Management System, the MES must be capable of dynamically defining calculated recipe parameters prior to processing a lot at a given piece of equipment and process step. While a simple parameter calculation can be performed by a business rule, the MES must support complex calculations with the capability to connect and interact with a separate dedicated application (e.g.: Matlab).

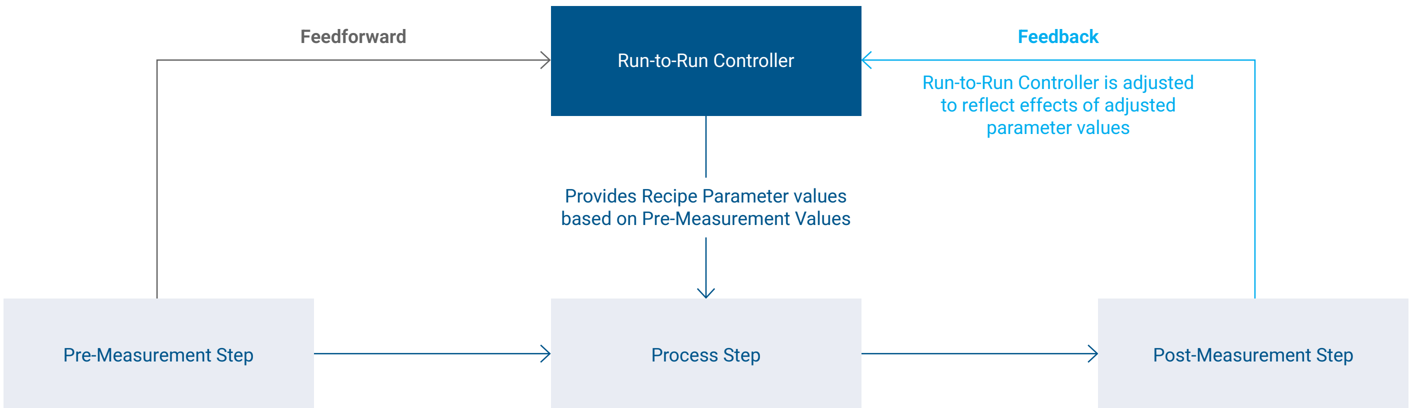


Fig. 4 Run-to-Run control using both feedforward and feedback

Chamber-Dependent Recipes

The Challenge

It is common in semiconductor front-end manufacturing that some equipment consists of multiple chambers with different capabilities. Certain processes require multiple chamber capabilities, so the composite higher-level capability at the overall equipment can only be considered to be available if the required chambers are available. When one or more available chamber provides the same capability, there are different possible combinations to realize the same process in the equipment. The recipe typically defines the specific chambers and chamber sequence to be used for processing, so the recipe availability is also tied to the available set of chambers.

The Solution

The MES must provide a capability-matching dispatch mechanism where lots require process capabilities and equipment provides them. The equipment capabilities, in turn, must be automatically linked with the availability of a specific set of equipment chambers. When processing a lot at a multi-chamber equipment that provides the required process capability, the system must provide a way to select the desired chamber sequence in MES to ensure that that the right recipe is used in the case that there are different possible chamber combinations.

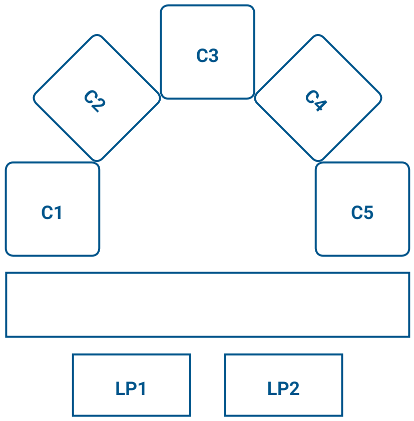
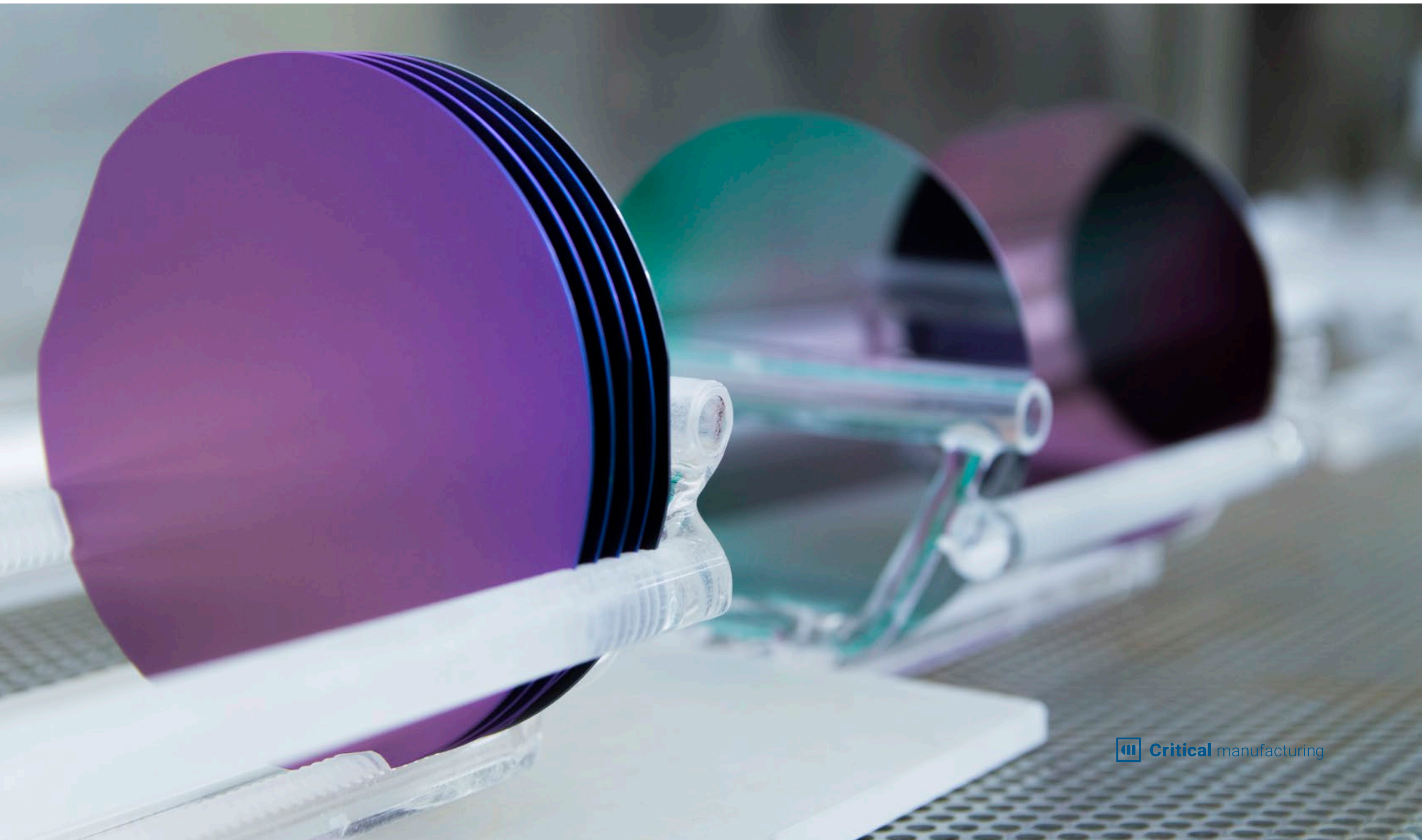


Fig. 5 Equipment with two load ports and five chambers (of three different types)



Reticle Management

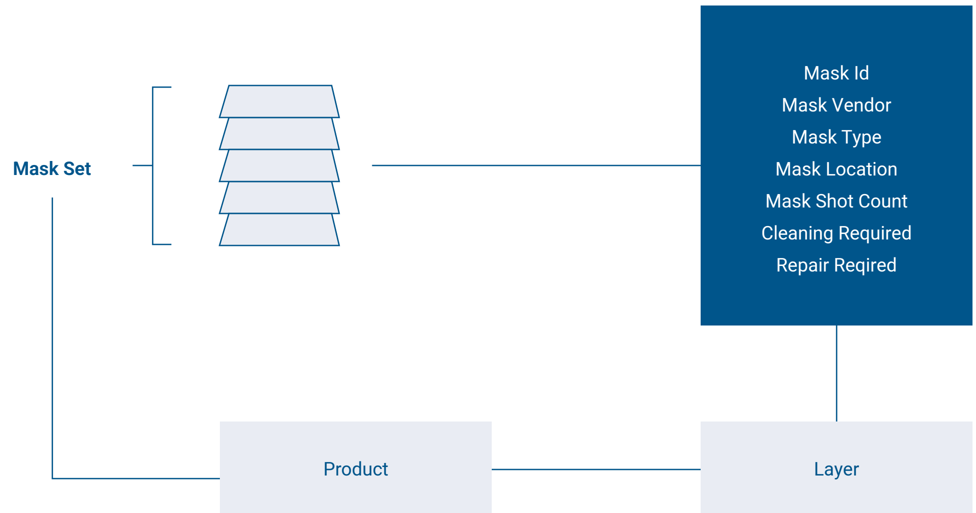


Fig. 6 Mask tracking

The Challenge

Each product requires a specific type of reticle or mask at each layer, and all the masks required for all layers of a product is called a mask set. Ideally, the mask set must be managed together as single element. It's important to ensure that the right reticle is used for the right lot at a specific step and equipment, and that the used reticle is captured in a system for traceability reasons. The physical location of each reticle must also be tracked, as well as its lifecycle, since they may be restricted to a certain number of shots, and it may require cleaning or repair to extend its lifecycle. In cases where scheduling is used, the system must be able to book the available reticles for different jobs. There is a minimum level of tracking required for a reticle or mask, as illustrated in Figure 6.

The Solution

The MES must provide a mechanism to link mask sets with a product and its different layers and process steps where each specific mask must be used. The mask set must be defined and managed together as one element. The MES must enforce that the correct mask is used at the right step and equipment. In addition, the MES must track and enforce the reticle maintenance lifecycle including its usage counters. The MES must also capture used masks for traceability reasons. When generating a schedule, the MES must be capable of allocating the available set of masks to different process jobs.

Send-Ahead Wafers

The Challenge

Because some processes are critical and present some risk to the lot, it's very common to use a send- ahead wafer to check the quality of one or more processes, at one or more pieces of equipment, before processing the remainder of the lot. If any problem is detected in the send-ahead wafer, it can be sent for rework, the process and/or equipment can be adjusted, and another send-ahead wafer will be used until the process is confirmed to be within the specified tolerances. Once the send-ahead wafer results meet the desired specifications, the remainder of the lot can be processed with the same equipment and processes, as shown in Figure 7. It should be possible to configure send-ahead wafers for certain products at certain processes, as well as for experiments.

The Solution

The MES must support the creation of a send-ahead run that includes the definition of the send-ahead wafer, as well as the definition of the lot (or group of lots) that cannot be processed until the send-ahead wafer successfully passes a measurement step. In cases when a send-ahead wafer fails a measurement step, the send-ahead run must be modified so that a new send-ahead wafer can be taken. The MES must take care of all the splits and merges, using sorter integration when required.

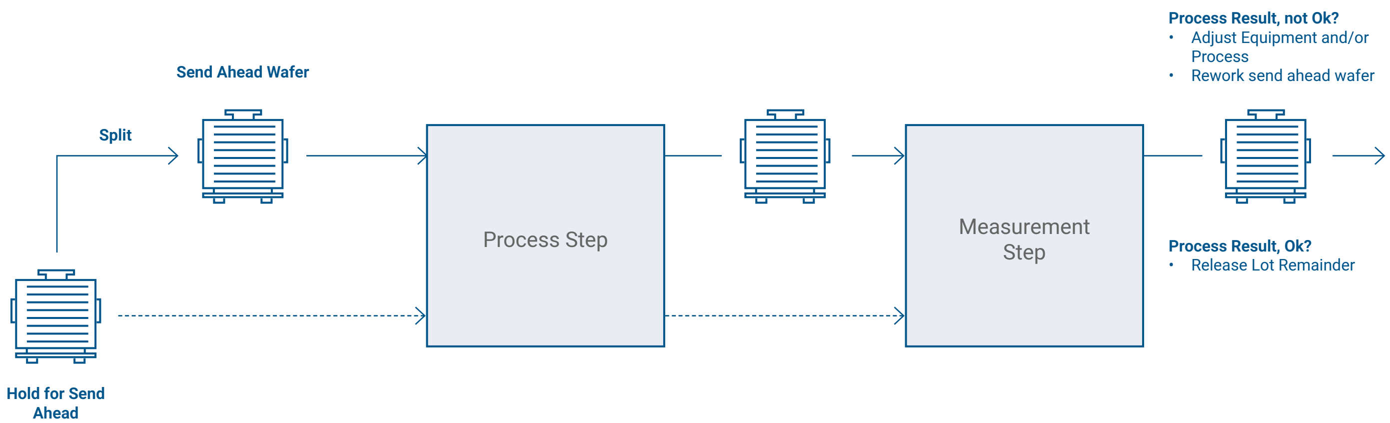


Fig. 7 Send Ahead Wafer

Sorter Integration

The Challenge
In front-end semiconductor 300mm and 200mm fabs, wafer handling is typically performed using specially dedicated equipment called sorters. Sorters are only concerned with carriers and wafers, not lots. Sorters can perform a variety of operations as described in Table 1.

Sorter operations may be planned and defined as part of the process plan or unplanned in which case they need to be required ad-hoc. Sorter job requests must include all the required information which varies depending on the sorter operation. In any sorter operation, the MES must keep the lot-wafer-carrier-slot information up to date.

The Solution
The MES must provide the capability to create sorter jobs, and it must support the different types of sorter operations that require different types of information. The MES must also support sorter operations that are planned in advance as well as ad-hoc sorter operations. To carry out the sorter process, both the lot and respective carriers must be moved to a sorter step and to a sorter equipment. In addition, integration with sorter equipment is required to automatically update the lot-wafer-carrier-slot information in the MES.

Operation	Description
Scan	Reads the Wafer Id for every slot in a carrier.
Split	Splits the content from one carrier into one or more carriers.
Merge	Merges the content from two or more carriers into one.
Transfer	Transfers the content from one carrier to another.
Compose	Transfers wafers from multiple carriers into another.
Sort	Changes the slot map inside a carrier by performing one of the following sub-operations: • Randomize – puts each wafer in a random slot • Compress – removes empty spaces in the carrier • Invert – inverts the position of the wafers in the carrier • Set Slot Map – sets a specific position for each wafer in the carrier
Flip	Flips the wafers inside a carrier

Fig. 8 Sorter operations

Equipment Qualification and Non-Productive Wafer Management

The Challenge
It's important to ensure that both the equipment and the equipment processes are qualified before processing productive material. There are certain equipment qualification procedures that must take place periodically, or when certain conditions occur (e.g. after a maintenance operation). Therefore, is must be possible to define a list of equipment capabilities, qualification procedures, trigger conditions for each equipment, and the qualification state for each equipment must be maintained as well. If an equipment capability is not in a qualified state, that capability cannot be used for production lots.

Some qualification procedures require the usage of qualification lots that consist of different types of non-productive wafers. The qualification lot must be composed using a sorter. The wafers must then be measured, the qualification process run, and the wafers measured again to ensure that the process is qualified. The qualification lot is then dismantled by separating the wafers according to their type and measurement result. Once a wafer carrier is full, it may be re-used, recycled or reclaimed depending on the measurement results and recycling counters.

The Solution
The MES must keep a list of qualification procedures for each piece of equipment, together with their triggers and must also define the composition of the qualification lot. The MES must track the qualification state of every equipment at all times and automatically trigger the different qualification procedures (e.g. time intervals or maintenance activities). If there is a pending qualification for a piece of equipment, the MES must ensure that the production material cannot be processed until it has been properly qualified. The MES must also support the creation of qualification lots and their associated qualification procedures. After the qualification, the MES system must store the qualification wafers and send them for reuse, recycle or reclaim.

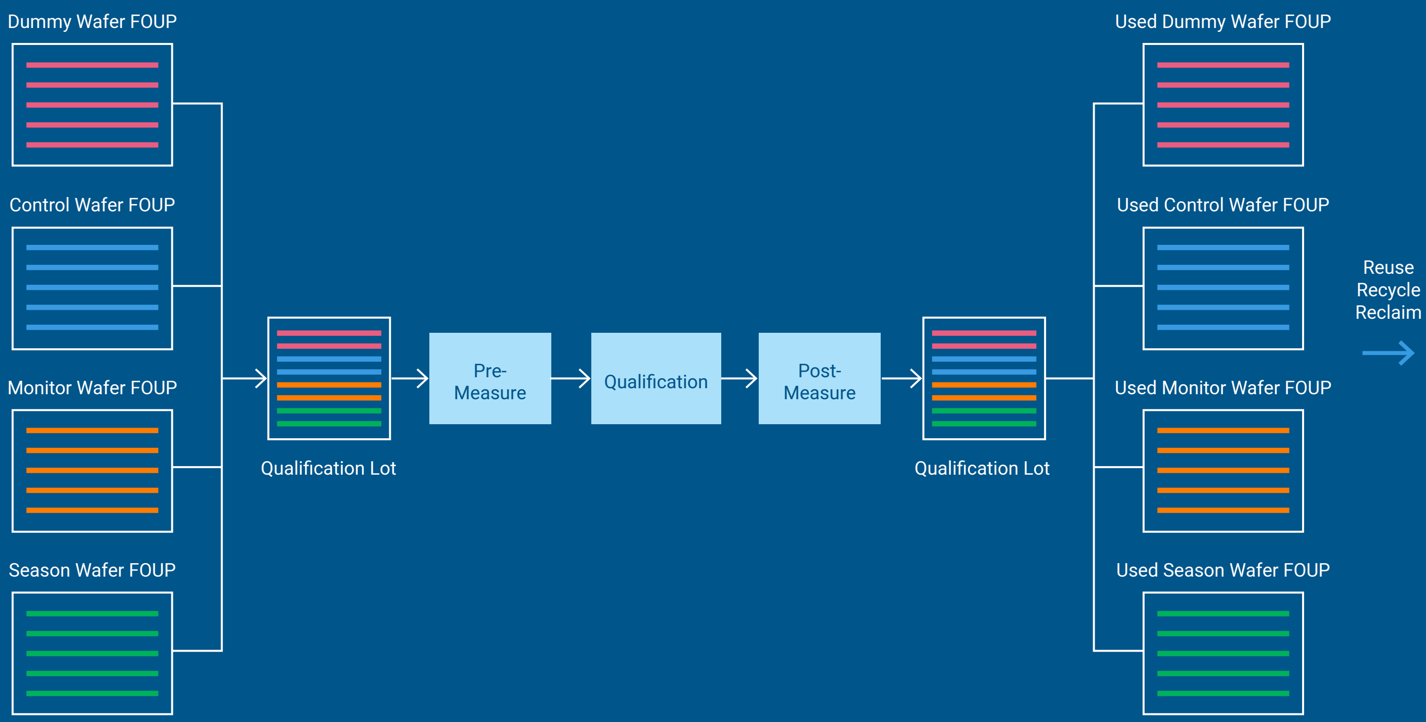


Fig. 8 Equipment qualification scenario

Contamination

The Challenge

When manufacturing different types of products that use different types of materials (e.g.: copper or nickel), cross-contamination of lots, carriers and equipment must be avoided. The contamination class for different materials must be specified as determined by a combination of the D-Factor (detrimental impact), C-Factor (control) and X-Factor (exposure). It is also necessary to restrict carriers and equipment by contamination classes, as shown in Figure 9.

It's important to track the current contamination level of a carrier because it becomes progressively more contaminated after being processed across different equipment. After a carrier is cleaned, the contamination level must be reset back to zero.

The Solution

The MES must keep track of carrier and equipment contamination classes and also contamination levels. It must also support the definition of a compatibility matrix between different contamination classes, including contamination levels. When a carrier is used throughout the fab, either by having material assigned to it or by being processed at a piece of equipment, the MES must automatically increase its contamination levels. The MES must also enforce compatibility between the carrier and equipment at all time. As part of the maintenance cycle, the contamination level of a carrier must be reset after cleaning.

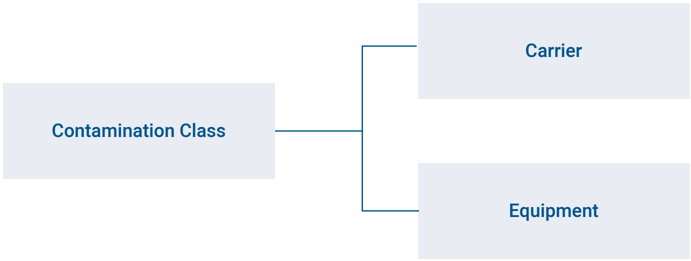


Fig. 9 Contamination class compatibility

Sampling

The Challenge

Metrology operations are expensive and not every lot or wafer gets measured every time. There are two types of sampling: Lot-based sampling and Wafer-based sampling, as shown in Figure 10.

Lot-based sampling consists of defining a sampling strategy at the lot-level. This strategy can be time or counter based and it's based on flexible context (e.g. for Product P1, measure one out of every 10 lots and for equipment Litho-01, measure one lot every four hours). There may be several consecutive metrology steps (e.g: Critical Dimension and Overlay) that are subject to Sampling. Thus, it's not only a matter of deciding if a given lot must be subject to metrology or not, but it's a matter of deciding which metrology steps must the lot go through.

Wafer-based sampling is applied when a lot is already at a metrology step. This sampling strategy is used to define which specific wafers must be measured. A common scenario is to measure one wafer per chamber from a previous process equipment.

The Solution

For Lot-based sampling, the MES must support the definition of sampling evaluation steps and lot-sampling strategies (e.g. based on time or counters) for different process contexts. Based on the lot-sampling strategies the MES system will evaluate and assign the sampling steps for each lot.

For Wafer-based sampling, the MES system must support the definition of wafer-sampling strategies at particular metrology steps, so that when a lot is moved to that step, the system determines exactly which wafers must be measured.

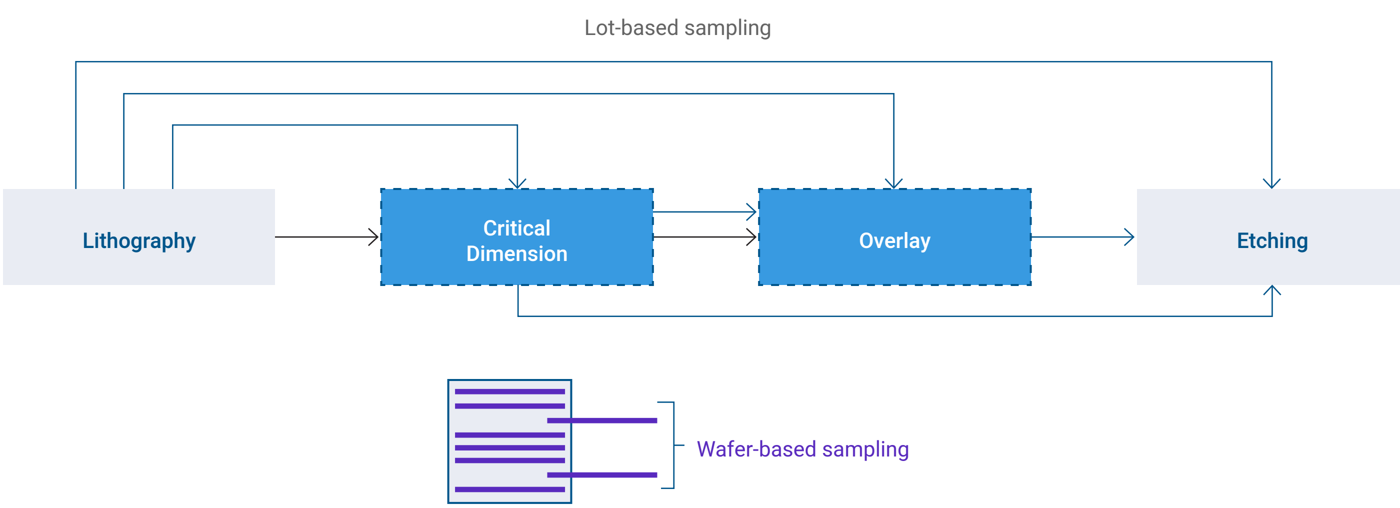


Fig. 10 Lot-based and wafer-based sampling

Process Queue Time Constraints

The Challenge

Some front-end manufacturing processes are time sensitive, and quality can be compromised if the time between two process steps is exceeded. Process steps are not necessarily consecutive which means that the point-in-time events for which a time constraint must be established between two process steps may be different, as shown in Figure 11. In addition, there may be multiple time constraints active at the same time for the same lot. It may be useful to get a heads-up warning as an opportunity to expedite some activities, and in the case that a time constraint is exceeded, a corrective action may need to be performed, such as placing the lot on hold or sending the lot for rework. It is important to ensure that defined time constraints cannot be violated.

The Solution

The MES must support the definition of process queue time constraints between any process step and define business rules to be triggered when a warning time or error time is reached. The system must enforce that the process queue time constraints are not violated and it must initiate the warning and error business rules whenever the respective times are reached.

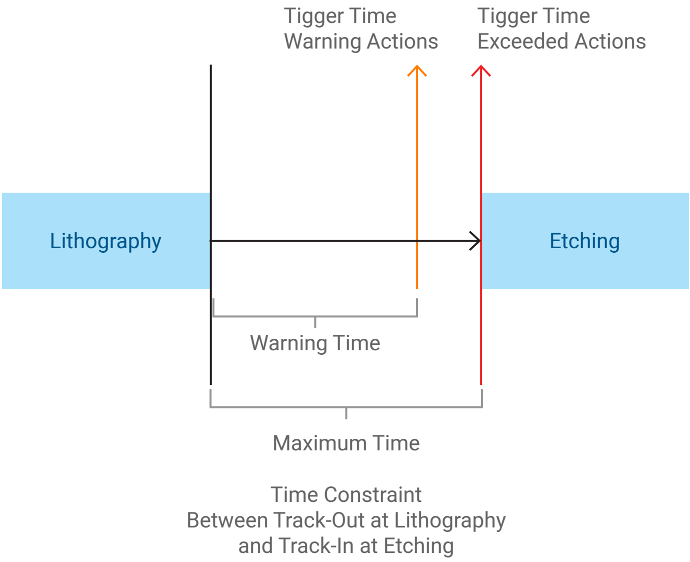


Fig. 11 Process time constraint example

Equipment Dedication

The Challenge

There are process steps, such as lithography, where for certain critical layers, it is required that the lot is processed in the same piece of equipment that was used to process the same lithography step in a previous layer, as shown in Figure 12.

During design of experiments (DoE) it's also normal to enforce that a lot, or set of wafers, is processed at a specific piece of equipment at a particular process step. Thus, it must be possible to define in advance where in which equipment a lot will be processed at a certain process step, either in a dynamic manner, such as with critical lithography equipment, or in a static manner, such as with an experiment. It is important to ensure that equipment dedication is enforced both by dispatching and scheduling.

The Solution

The MES must support a generic mechanism to set the equipment to be used to process a lot at a particular process step in advance. This mechanism can mark a process step as being critical, so that whenever a lot is processed at a piece of equipment, the system automatically sets it for the next time the lot is processed at the same step, even if with a different context (e.g. at a different layer).

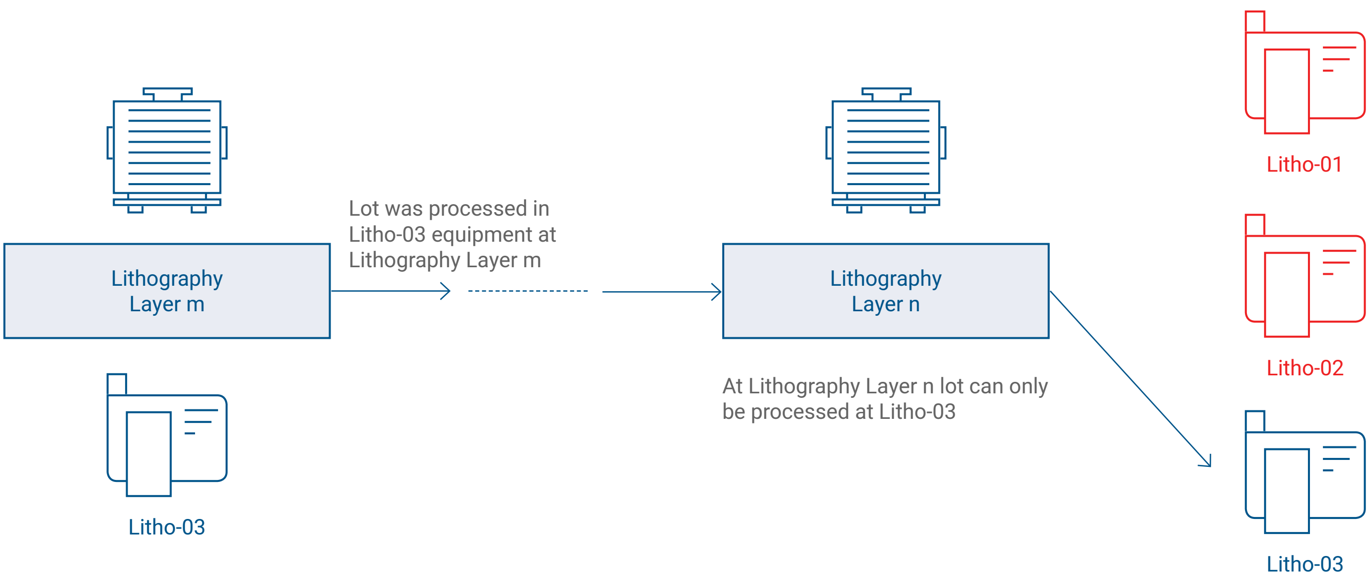


Fig. 12 Dynamic equipment dedication example

Conclusion

As technology rapidly advances, semiconductor chip manufacturing has become an enormous undertaking, with many new products requiring advanced process capabilities. Semiconductor Front-End manufacturers need to increase utilization, balance volume production throughput with high yields and at the same time reliably develop and ramp new products.

Modern Semiconductor MES provides the flexibility and capabilities to handle extremely complex advanced manufacturing scenarios, improve the speed of learning while increasing quality and lowering costs. Modern MES provides expanded functionality in a single system, to allow companies to keep pace with rapid changes while providing a foundation to support the future of semiconductor manufacturing.

About the Author

João Cortez holds a Computer Science Engineering Degree from University of Minho. He began working with MES in the semiconductor industry in 1997 and he has held different positions related with manufacturing software and software architecture. He is one of the founders of Critical Manufacturing having held the role of Product Manager since joining the company in 2009. As a Product Manager, João has led the CMF MES product design and roadmap.

About Critical Manufacturing

Critical Manufacturing provides the most modern, flexible and configurable manufacturing execution system (MES) available. Critical Manufacturing MES helps manufacturers stay ahead of stringent product traceability and compliance requirements; reduce risk with inherent closed-loop quality; integrate seamlessly with enterprise systems and factory automation and provide deep intelligence and visibility of global production operations. As a result, customers are Industry 4.0-ready. They can compete effectively and profitably by easily adapting their operations to changes in demand, opportunity or requirements, anywhere, at any time.

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