NANOCHIP FAB SOLUTIONS
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IMPROVING YIELD WITH FLEET CHAMBER MATCHING

CHAMBER MATCHING REQUIRES MULTI-DIMENSIONAL SOLUTIONS

Matching tools running identical processes is particularly critical for users migrating to more advanced nodes (<28nm). Sustaining a fleet of tools to a matched state can reduce yield losses and yield variability, allow for greater routing flexibility in the fab, identify and control process inefficiencies, and reduce time for root cause analysis of yield issues. Applied Materials understands the criticality and complexity of chamber matching, and is leveraging its algorithmic, equipment- and process expertise to develop a comprehensive solution that enables matching across many dimensions.

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Ideally, the matching process would extend to every available dimension, from configuration through process setup and execution, and yield analysis, as shown in figure 1. The first step in the matching process is to perform a hardware and software audit. In many cases a "golden tool" is identified as part of a collaborative effort between the customer and Applied experts. Baselines for the hardware and software parameters are established using Applied's tool- and process expertise. For example, we can help determine what parameters are important to the matching process and what level of matching needs to be obtained.

After the hardware and software configurations are matched, tool sensors and data collection come next. Applied E3 data collection and analysis configurations are matched and E3 analysis capabilities such as "chamber variance reporting" are used to determine the level of chamber matching and to investigate sources of mismatch, as shown in figure 2. Often the remedies involve identifying underperforming chambers and then matching input and output parameters to "golden" chambers. For example, in a poly etch matching process, drive current (I_{on}) matching was improved from a difference of 7% to 0%. Ion standard deviation within wafer was reduced by 30%. This was achieved by matching gas flows, equipment constants, RF parameters, and recipe optimization. As a result, chambers that were previously performing poorly were returned to production.

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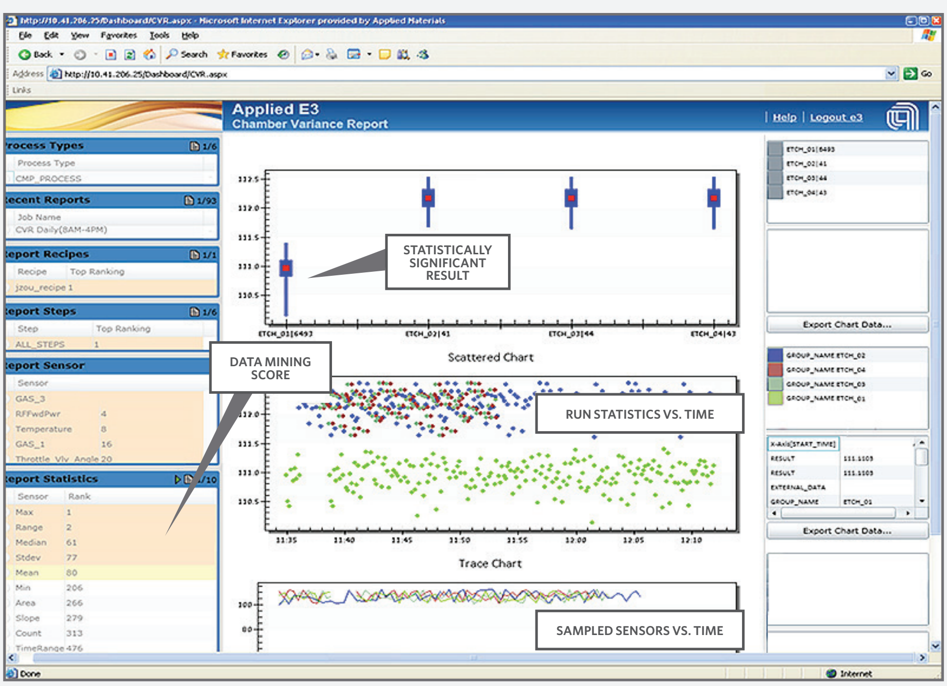
TAKING THE NEXT STEP: CHAMBER VARIANCE CORRECTION DURING PRODUCTION

The capabilities identified above are critical to the chamber-matching process and yield a number of benefits. However they are generally applied offline and don't address chamber matching during production (see the dark blue steps in figure 1). In examining how to improve this technology and provide chamber variance correction during production, we realized that current approaches do not provide the control recommendations or actions required to bring operating chambers closer to a matched state; rather they provide insight into what is "wrong" and leave it to experts to determine what should be modified. While this approach is appropriate for certain dimensions of the chamber-matching problem, such as hardware, software and sensor matching, it does not work as well during production where matching decisions are often made lot-by-lot or even wafer-by-wafer. As is noted in the ITRS, what is needed is "migration of Chamber Variance Reporting to Chamber Variance Correction Systems...." [1] Fortunately, the same software tool used for chamber variance investigation, E3, is being enhanced by Applied engineers to provide these automatic correction capabilities. The challenge is determining an algorithmic approach to chamber variance correction.

1. Hardware Configuration	• Mainframe, Chamber Variant • Upgrades • Facilities
2. Software Configuration	• Software Revision • System Constants
3. Tool Sensors	• FDC Traces for P1 Sensors • Sampling Frequency
4. Process	• Recipes • Process Window
5. Metrology	• Target • Uniformity • Defect
6. Maintenance	• PM/CM Practice, Calibration • Parts & Cleans • Maintenance History
7. End-of-Line Electrical	• Parametric • Yield

Figure 1. Chamber-matching dimensions.

As Applied experts looked into this problem, we first noted that a common definition applied to chamber matching is "matched outputs" as measured by post-process metrology. Using this definition, chamber matching can be achieved by setting the E3 run-to-run (R2R) control



The top graph summarizes chamber variance per chamber across the fleet and indicates an unmatched chamber. Root cause investigation: On the lower left a data mining score indicates which parameters are important to the chamber mismatch; in the middle graph summary data on these important variables can be compared over the course of many runs; on the bottom graph the sensor raw data can be analyzed and compared.

Figure 2. Chamber variance reporting with E3.

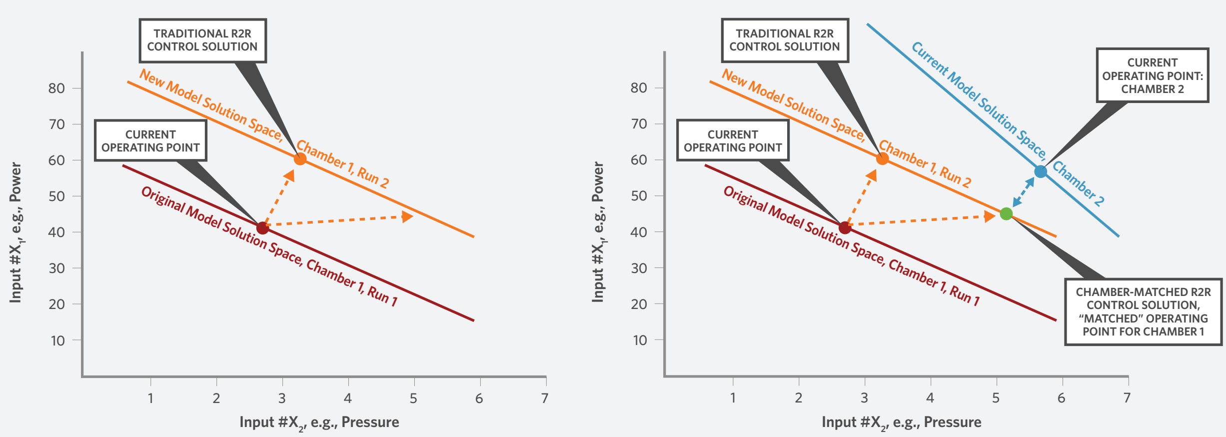
targets (e.g., thickness and uniformity) to be equal across the fleet. Using this approach (which we do with E3 today) the chamber outputs can be "matched"; however the chambers can be operating very differently (e.g., high temperature with lower time settings for chamber 1 and lower temperature with higher timer settings for chamber 2 producing the same thickness output). This can cause yield variability and ultimately yield loss.

An improved definition is: "chambers are matched if their states of operation are matched." This requires that, in addition to matching process outputs, we should also try to match process conditions such as process inputs and process variables. Thus, in the above example, temperature and time setting inputs should be matched in addition to thickness output.

In order to provide improved matching during production with this amended matching definition, we are working to develop a fleet-wide matched R2R control approach.[2] The approach leverages Applied's E3 capability for fleet-wide monitoring and coordinated control. It also leverages the fact that, in many R2R control solutions, the control problem is "underdetermined"; that is, there are more tunable inputs (e.g., time and temperature) than outputs to control (e.g., thickness) and so there are technically an infinite number of control solutions. With this approach, a fleet target R2R control recipe (i.e., a recipe consisting of R2R control adjustable parameters) is determined utilizing R2R control information across the fleet of tools to be matched. Depending on the matching goals, this target R2R control recipe can take many forms, including (1) a baseline recipe for a golden tool, (2) the latest R2R control recipe for that golden tool, and (3) a weighted "average" control recipe across the fleet of tools. The latter can be determined from an averaging of R2R recipe advices or an inversion of an average model across the fleet of chambers. When recipe advice is requested from a particular chamber, the E3 R2R controller picks a recipe that is closer to the target R2R control recipe (among an infinite set of choices), as shown in figure 3. The target R2R control recipe is updated as necessary. Relative weighting of variables (among inputs, and between inputs and outputs) can be used to skew the matching process toward variables that are determined to be more important to yield matching. With this approach R2R control is used to match process-tunable inputs in addition to process outputs. Thus the states of the chambers are kept closer together, leading to a better matched fleet.

We are also developing a method for extending the improved matching through the maintenance cycle, again using the extensive powers of E3. A number of E3 advanced process control (APC) tools are leveraged throughout the entire maintenance cycle as shown in figure 4. Equipment health monitoring (EHM) is used during production to monitor tool health and during the maintenance recovery process to assess "fingerprints" indicating successful maintenance procedures.[3,4] Predictive maintenance (PdM) is used to predict a consistent downtime state.[3] Virtual metrology (VM) and R2R control can be used to determine settings during maintenance recovery. Collectively these capabilities result in improved mean time between interrupt (MTBI) and mean time to repair (MTTR), and an opportunity to provide improved chamber matching through the maintenance process.

The collective use of these tools to provide maintenance cycle benefits is best illustrated through an example. In a thermal process, the lamp maintenance effort can be costly and time-consuming. In a typical system lamps can fail unexpectedly causing unscheduled downtime and scrap. The maintenance recovery can be time-consuming because there are usually multiple post-maintenance (i.e., after lamp kit replacement) iterations of lamp parameter "tuning" that include running a number of test



In this example we are controlling a single output, e.g., thickness, by tuning two input variables: power and pressure. We have a simple linear model of the chamber and a current operating point (left graph, red line and dot). With traditional R2R control, after a run, the R2R controller identifies a difference between the predicted output and actual output, adjusts the model accordingly, and selects a new operating point that is closest to the previous one (orange line and dot). In chamber-matched control with a fleet of two chambers (right graph), we are aware of the model and operating point for chamber 2 (blue line and dot). In this case, after updating the model for chamber 1, we choose an operation point (among an infinite set of choices on the line) that is closer to the operating point of chamber 2 (orange line and green dot).

Figure 3. Illustration of fleet-coordinated R2R control.

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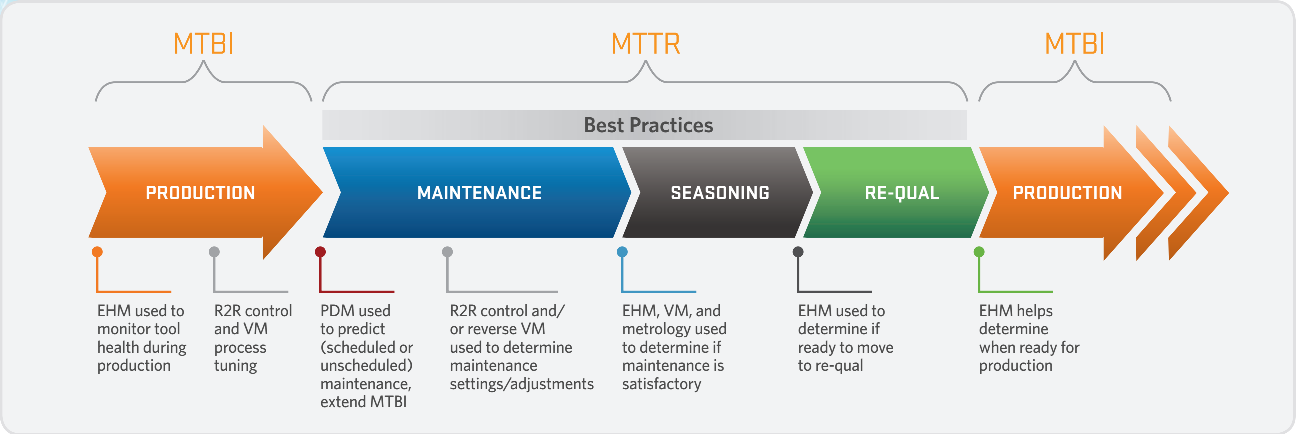

Figure 4. Utilizing Applied E3 capabilities for improved matching through the maintenance cycle.

wafers with specific characterization recipes, analyzing metrology data, and making hardware and software adjustments. Four to ten iterations of this type are not uncommon, leading to MTTR on the order of two days or more. In addition to all of these cost-of-ownership issues, there generally is no clear methodology for matching chambers through the maintenance process.

Applied engineers are enhancing E3 and E3 services so that these issues can be addressed to reduce unscheduled downtime and scrap, improve MTBI, reduce MTTR, and match chambers throughout the entire maintenance cycle. First E3 EHM will be used during production to monitor equipment health and point to any unforeseen lamp (or other) issues as they appear. As the lamp begins to degrade, E3 R2R control can be used to keep the process tuned so Cpk remains high. The R2R matching mechanism described above will be employed to keep chambers matched as much as possible during this lamp-degradation phase. E3 PdM models will predict a time horizon for lamp failure, allowing for the conversion of unscheduled maintenance to scheduled maintenance. A confidence factor provided with the prediction can help determine the "best" future state at which to bring the chamber down, based on an evaluation of the customer's relative costs for scheduled and unscheduled downtime. This "best" state will be matched across chambers. During the maintenance procedure, models relating the lamp-tunable settings to metrology data associated with the post-maintenance characterization runs will utilize multivariate R2R control and reverse virtual metrology to determine necessary lamp adjustments. This reduces the number of post-maintenance tuning iterations from 4–10 down to 2 or 3. Note that R2R controller matching can be employed here as well to better match the chambers as they return to production. Finally EHM can be used to verify a "fingerprint" of a healthy and matched tool that is ready for production.

MAKING IT WORK: A PARTNERING OF EXPERTISE

Effective chamber matching requires the leveraging of equipment, process, sensor and statistical knowledge. This can only be achieved if Applied works closely with customers to design, develop, implement and maintain chamber-matching solutions that are customized to be most effective for each unique situation. This advanced services-oriented approach to delivering solutions represents the new paradigm in APC. Indeed, the upcoming 2013 ITRS Roadmap, Factory Integration (FI) Chapter states:

> Development and maintenance of emerging capabilities such as PdM, VM, waste management, and utilities management incorporation into fab objectives, requires intimate knowledge of the fab objectives, process, equipment and the capabilities themselves. Thus it has become clear that cost-effective development and maintenance of these capabilities will require increased and continuous cooperation of users, OEMs and 3rd party FI capability suppliers.[5]

Applied Materials recognizes this need and, through its Applied Global Services business, is developing advanced services for multi-dimensional chamber matching. We will work closely with customers to deliver fleet chamber-matching solutions that (1) address all aspects of the chamber-matching problem and (2) are tailored to customer-specific needs.

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[1] *2012 International Technology Roadmap for Semiconductors (ITRS): Factory Integration Chapter, 2012 (available at www.itrs.net).*

[2] *J. Moyne, J. Iskandar, "Matching process controllers for improved matching of processes," United States patent pending*

[3] *J. Moyne, J. Iskandar, P. Hawkins, T. Walker, A. Furest and B. Pollard, D. Stark and G. Crispieri, "Deploying an Equipment Health Monitoring Dashboard and Assessing Predictive Maintenance," Proceedings of the 24th Annual Advanced Semiconductor Manufacturing Conference (ASMC 2013), Saratoga Springs, New York, May 2013.*

[4] *J. Moyne, J. Iskandar, B. Schulze, "Portable adaptable equipment health user interface," United States patent pending*

[5] *2013 International Technology Roadmap for Semiconductors (ITRS): Factory Integration Chapter DRAFT, 2013 (final version to be available at www.itrs.net in early 2014).*

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