Moving into the Predictive Space with Virtual Metrology

Metrology plays a crucial role in manufacturing. However, given its high capital equipment cost and cycle time impact on critical processes, metrology is a high-cost, high-stakes proposition. Further, issues with performance of metrology systems can lead to additional manufacturing cost and waste. These issues include lack of ability to support wafer-to-wafer metrology, delays in metrology data feedback, and lost productivity from non-optimal process control and lack of optimized metrology strategies.

Virtual metrology (VM) is a new technology rapidly gaining acceptance in the marketplace as an efficient and cost-effective way to optimize metrology value. It is less costly than conventional metrology, provides information much faster, and can work in tandem with conventional metrology to enhance the overall metrology performance.

VM is a modeling and metrology prediction solution whereby process and product data, such as in situ fault detection (FD) information and upstream metrology information is correlated to post-process metrology data. This same data can then be used to predict metrology information when conventional metrology data is not available. And a conventional metrology system augmented with VM can provide significant benefits (see Table 1). Indeed, the International Technology Roadmap for Semiconductors (ITRS) identifies VM as an increasingly critical technology for improving productivity and reducing waste [1].

Benefit	Approach
Reduced cost of metrology (capital and cycle time costs)	Replacing portion of metrology with VM (reduce capital cost) "Smart Metrology": utilizing VM to determine when actual metrology is needed (reduce cycle time cost)
Improved product quality and yield Improved run-to-run (R2R) control process capability Reduced R2R control process variability	Augmenting existing metrology (filling in the "gaps" due to no metrology measurement or delay) Incorporating virtual metrology data into R2R control schemes for move to full feed-forward/back wafer-to-wafer control Utilizing virtual metrology techniques for yield prediction
Reduced product waste and equipment downtime	Utilizing VM data in fault detection schemes Utilizing VM to reduce need for non-product wafers
Predictive maintenance Rapid maintenance qualification	Using VM to better determine when equipment maintenance is needed Determining quality of maintenance operation through VM prediction of product quality Using VM to more rapidly determine when tools are qualified for production after maintenance

TABLE 1. Benefits achievable with virtual metrology and the approach taken with existing metrology and other factory systems to achieve these benefits.

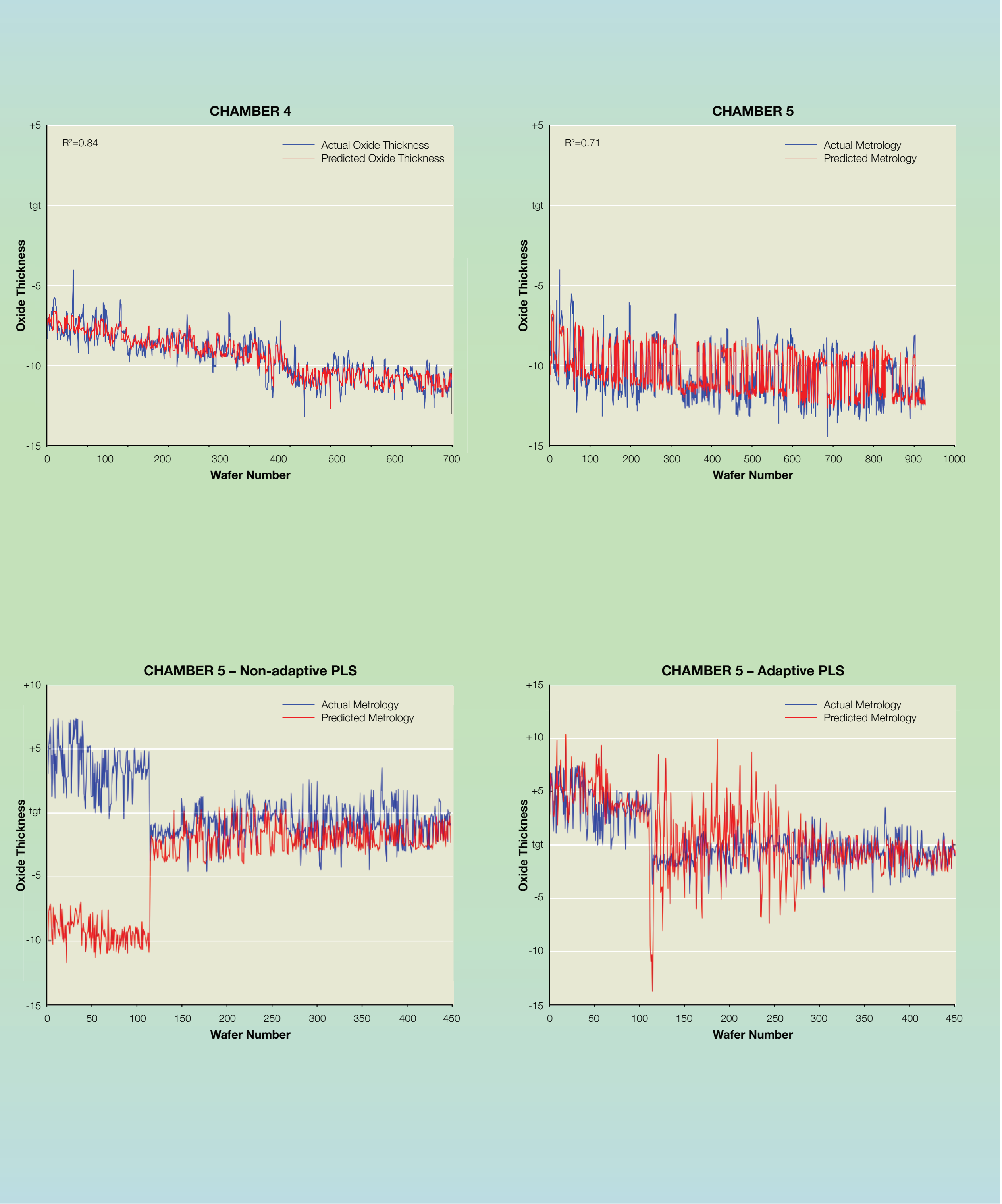
HOW DOES VM WORK?

VM is an advanced software solution that utilizes process and product information, normally collected through fault detection applied to a process, to analyze and predict product quality information. Historical fault detection, process, and metrology information is first collected for a given process in order to support model development. If resources are available, design of experiments (DOE) data can also be used to facilitate this model discovery process. The information is used to develop base VM models leveraging techniques such as partial least squares-project on latent structures (PLS).

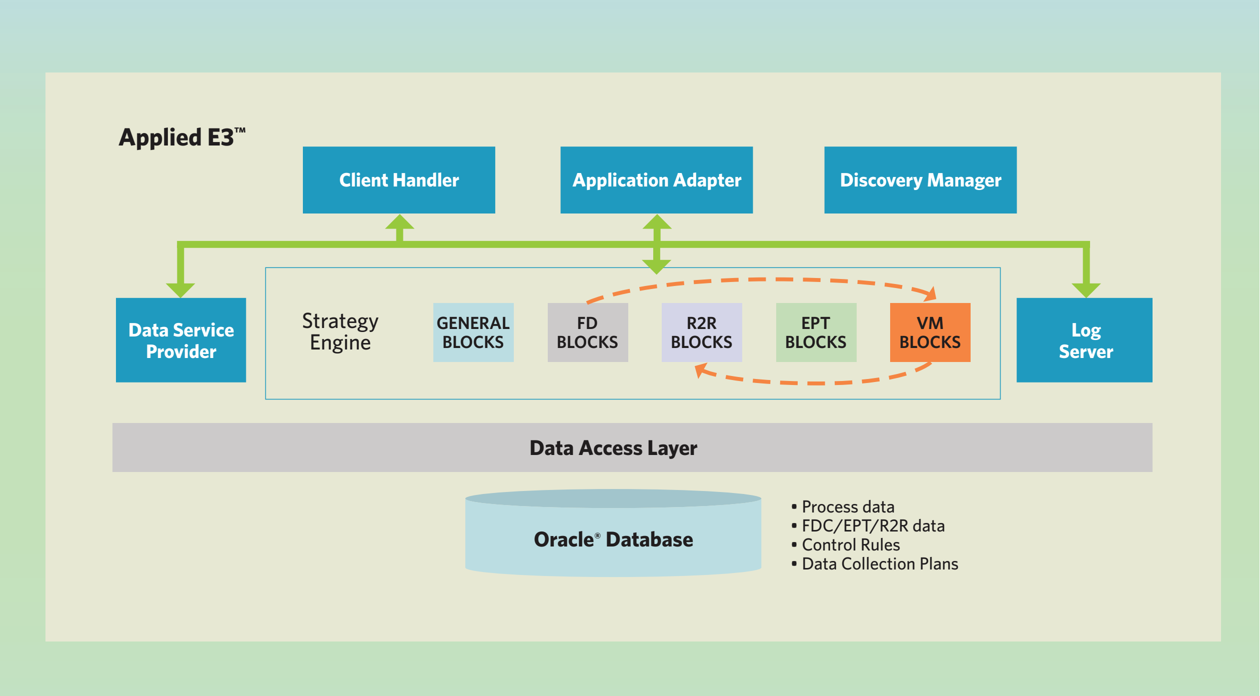
Trace data can be used instead of, or in addition to, fault detection information to support PLS modeling; however, based on Applied Materials' experience, the complexities of model maintenance during run-time make the use of trace data on a run-to-run (R2R) basis somewhat impractical. Reduced data from FD models is sufficient to support high quality prediction models.

The base prediction models produced by PLS modeling are non-adaptive. In order for these VM base models to be effective we must add an adaptability capability—in other words, the models must be able to adapt to the dynamics, such as drifts and shifts, that are typically found in semiconductor processes. Many methods have been proposed for addressing these issues. Applied Materials has found that different methods are best suited to adapting to different dynamics. As a result, Applied has developed a unique adaptive VM capability. It includes a methodology that allows the VM system to "switch" between adaptation methods based on the process dynamics, thus providing significantly better prediction capabilities.

As an example of a practical VM application, Figure 1 shows sample results of a pilot study with Micron Technology, applying VM modeling to six chambers of a CVD process[2]. The metrology values for each chamber were predicted with a high degree of accuracy using VM models derived from process FD data. Further, the adaptive VM approach was shown to be an improvement over non-adaptive VM.



▲ **FIGURE 1.** Results from a virtual metrology pilot project with Micron Technology. The top graphs illustrate the ability of VM to model two chambers. The bottom graphs illustrate that adaptive virtual metrology (right) can better track process dynamics (in this case a process shift) than non-adaptive virtual metrology (left). The noise in the data just after the process shift near wafer 110 illustrates the need for methodology that allows the VM system to switch between adaptation methods (a single adaptation method was used in this pilot study).



▲ **FIGURE 2.** Vision of virtual metrology within E3 illustrating integration with FD and R2R components.

INTEGRATING VM WITHIN A FAB AUTOMATION SYSTEM

While VM can clearly reduce cost and improve productivity, obtaining high ROI from VM implementations requires full integration within a fab automation system so that the technology is reconfigurable and reusable. Since VM uses FD information to provide predictions, and since R2R control is one of the major consumers of VM information, the fab advanced process control (APC) automation infrastructure is the logical place to incorporate a flexible VM capability.

Applied E3™ is an APC automation solution that provides both FD and R2R control capabilities on the same SEMI E133 standard compatible platform. Thus, E3 is ideally suited to provide a VM capability (see Figure 2). VM "blocks" would just be another module provided in the E3 suite of capabilities alongside FD and R2R control modules. The VM blocks take FD output information from FD module "strategies" to make predictions. These blocks allow the user to select VM parameters to customize solutions and provide an adaptive VM capability that includes automatic switching between adaptation methods depending on process dynamics detected. VM strategies then dictate how the VM predictions are used (for example, export to R2R control strategies). The flexibility of the E3 strategy environment allows the user to harness VM to realize the benefits listed in Table 1.

LOOKING AHEAD

Applied Materials foresees a general movement from reactive to predictive operations in all manufacturing arenas. Fault detection will be replaced with fault prediction to further reduce scrap and equipment downtime. Predictive maintenance will augment preventative maintenance to further reduce downtime. Ultimately a fusion of real and virtual environments will take place, creating a virtual "copy" of the factory that operates alongside the real factory. The virtual factory models will be continually updated with real data and used to predict all aspects of future factory operations, reducing downtime and scrap, and improving throughput and yield. Virtual metrology technologies, along with other prediction capabilities such as scheduling and maintenance prediction, represent the critical first step toward a comprehensive predictive roadmap that we believe will inevitably lower costs and raise productivity for manufacturers of semiconductor, flat panel display and solar products. ■

REFERENCES

(1) *International Technology Roadmap for Semiconductors*, (2010), www.itrs.net.

(2) K. Olson and J. Moyne, "Adaptive Virtual Metrology Applied to a CVD Process," *Proceedings of the 21st Annual SEMI/IEEE Advanced Semiconductor Manufacturing Conference (ASMC)*, San Francisco, (July 2010).

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