Look ahead to the power of predictive service solutions.
Predictability isn’t one of those concepts people tend to get excited about. And it’s really no mystery why: when it comes to food, travel, entertainment and many other aspects of life, “predictable” can be boring.

But in the world of complex manufacturing where we live, predictability represents an incredibly exciting change in the way we do things. Ever since the semiconductor, flat panel and solar voltaic industries first emerged, many of the high volume production lines have been maintained using the “fail and fix” paradigm. This approach to equipment maintenance and support has resulted in some unwanted consequences, including unnecessary unscheduled downtime, scrap product, and lower overall fab productivity.

Now with the development of new technologies based on the prognostics and health management (PHM) model of equipment maintenance, a new and more productive paradigm is available. Instead of waiting for things to break, PHM models and features such as sensors, automation and remote diagnostics will help fab managers predict and prevent problems from occurring. Given the complexity of many manufacturing processes, the ability to detect and fix problems faster, and anticipate component failure and respond proactively will save fabs time, money and materials—and significantly improve their products, processes and ROI.

In this issue of Nanochip Fab Solutions, you will get a first look at emerging PHM technologies and the predictive models that support them. You will also learn how they are already proving themselves in real-world installations. For example, Jay Lee and Edzel Lapira of the University of Cincinnati Center for Intelligent Maintenance Systems describe how data-driven surge map modeling used to achieve $50K in energy savings for Toyota is adaptable to semiconductor manufacturing.

James Moyne discusses the predictability vision and roadmap in his story, “Incorporating Prediction in Next Generation Manufacturing,” and our Applied Global Services FabVantage consultants explore the benefits of developing models and running simulations before implementing changes on the line. By running real data sets pulled from the production floor, models are becoming more precise than ever, enabling benchmarking of equipment performance and faster troubleshooting at the component level. We also explore predictability in Solar manufacturing, with thoughts from Applied’s solar expert, Dr. Charlie Gay and others.

Despite our best efforts though, sometimes the unpredictable does happen. In “A Customer Story” you’ll read about the amazing recovery of Renesas following the catastrophic Japan earthquake earlier this year. And finally, journalist Dave Lammers wraps up with his look to the future and the long-predicted industry shift to 450mm manufacturing.

Predictability. It may not be exciting to some. But it is game changing for our industry. At Applied Global Services, we see predictability as the next step in helping our customers move closer to achieving the ultimate productive fab. We predict it will not be boring!
Over the past few years the manufacturing discipline has seen the beginnings of a major evolution in approach, namely the movement from reactive to predictive operations. In semiconductor manufacturing, the International Technology Roadmap for Semiconductors (ITRS) has also been updated, identifying “the movement from reactive to predictive” as a major trend in factory integration. The basic concept behind prediction in manufacturing is to utilize real-time manufacturing data to predict what will happen in the future, and then make decisions based on these predictions. With an automated manufacturing infrastructure enhanced with prediction, a significant number of benefits will be achievable including reduced unscheduled downtime, MTBF, MTTR and scrap, and improved uptime, life of consumables, yield, and throughput. This paper presents a roadmap for achieving these goals through a manufacturing prediction strategy.

The ultimate vision of prediction in manufacturing automation is an environment where prediction is in lock step with manufacturing. We can even take this vision one step further by considering how to empower the engineer with real-time simulation capability. This technology can be likened to your DVR where you can pause, rewind and replay a movie but also fast-forward to see how the movie will end. Such a capability will allow the user to leverage existing user interfaces and consider different scenarios in a “what if” fashion as a mechanism to make decisions and plan for the future. This capability will have enormous impact in maximizing fab capabilities, as well as improving ramp-up rates and the ability to adjust to changing business requirements.

ACHIEVING THE VISION: KEY PREDICTION CAPABILITIES

The full prediction vision must be achieved as part of an evolution rather than a revolution in manufacturing practices, because the latter would be too expensive and disruptive to implement. Thus we must devise a prediction roadmap containing solutions that are (1) aligned with the ultimate vision of real-time simulation and simulation matched with reality, (2) non-disruptive, and (3) strictly value added (as much as possible), with little or no downside risk on operations. The following are key prediction technologies that can be part of such a prediction roadmap.

Virtual Metrology

Virtual metrology (VM) is the process of using equipment and process information to predict metrology values, thereby avoiding much of the capital and throughput cost associated with measuring all wafers in an in-line metrology system. As shown in Figure 1, a VM system uses information provided by a fault detection (FD) system along with metrology, and context information (e.g., product type) to provide models that predict metrology values for a process. VM technology has already been shown to be quite effective in predicting semiconductor metrology data, and can provide a number of benefits, including (1) reduced capital cost of metrology, (2) increased throughput through reduced use of (actual) metrology, (3) improved process capability by enabling wafer-to-wafer control (as shown in Figure 1), and (4) reduced non-product and scrap wafers. Two separate studies have concluded that these benefits will amount to an average of over US $35M/year/fab.

Predictive Maintenance (PdM)

As noted earlier, unscheduled downtime is considered by many to be the number one source of lost revenue on the factory floor. Predictive maintenance (PdM) is the predictive process of utilizing equipment and process state information to predict impending unscheduled downtime events, thereby minimizing the occurrence of unscheduled downs. PdM leverages much of the same input data and modeling techniques of VM, and provides for reduction of unscheduled downs (by converting these downs into scheduled downs), as well as reduction of MTTR by providing...
an indication of the particular “fix” required; see for example Figure 2. Further, with a PdM system in place, conservative maintenance schedules can be relaxed, resulting in increased life of consumables, reduced environmental waste, and further increased uptime.

**Predictive Scheduling**

State-of-the-art, real-time scheduling and dispatch allows the fab to be highly responsive to changing conditions such as customer orders, inventories or fab equipment availability. However, this system is still reactive. Predictive scheduling, also called “short interval scheduling,” utilizes information on customer orders in the queue as well as upstream WIP information and equipment availability information to predict equipment availability and capability. It then schedules and dispatches WIP and production resources (e.g., reticles) accordingly to avoid cycle-time “white space” or “waist-time” waste, and improve throughput. Predictive scheduling has already shown to be very effective in improving key throughput metrics, and more importantly, improving throughput of high-priority lots to meet customer requirements.\(^{[39]}\)

**Yield Prediction and Control**

Yield prediction and control is the technique of using process, equipment and fab state information to predict yield and yield excursions, and then utilizing these predictions to control the operation of the fab to yield and throughput objectives.\(^{[40]}\) Using this yield prediction information, WIP scheduling, maintenance schedules and even advanced process control can be adjusted to avoid produce scrap, unnecessary downtime and low-quality product, and maximize yield-throughput objectives. The advent of yield prediction and control will represent the culmination of benefit of prediction in the fab as it ties prediction and operation to the key revenue generators of yield and throughput. (See Figure 3.)

**Moving Forward: Applied Materials Prediction Roadmap**

It is clear the industry is progressing to a predictive mode of operation so that benefits summarized in Figure 4 can be realized. Applied Materials is working to execute a prediction roadmap to achieve the industry’s predictive manufacturing goals. This includes the development of building blocks that, by themselves, can provide immediate and significant ROI. Collectively, as part of an integrated predictive automation solution, they will provide an even greater level of productivity gains. Applied RTD, our real-time scheduling and dispatch product, is one such example. SmartSched is an upgrade to RTD that provides predictive scheduling solutions which have been successfully deployed at customer sites,\(^{[41]}\) and will also be utilized in the development of PdM solutions. Applied E3 Advanced Process Control software is another building block currently being enhanced to provide VM and PdM solutions,\(^{[42]}\) and will be the cornerstone of our future yield prediction and control solution.\(^{[43]}\)

With critical KPIs like capital cost, downtime, productivity, yield and throughput on the line, prediction will be the key to manufacturing competitiveness. Achieving the ultimate vision—“prediction in lock-step with manufacturing”—requires extension of the entire automation value chain. Prediction solutions such as VM, PdM and predictive scheduling can generate high and immediate ROI and support the evolution of manufacturing, from reacting to disruptive production issues to predicting and resolving them before there is damage to products or profitability.

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PREDICTABLE DOWNTIME AND INCREASED THROUGHPUT ON CONSTRAINT TOOLS

IMPROVE TOTAL FAB OUTPUT

As discussed in a previous issue of Nanochip, the lot queue time and subsequently, cycle time of a high-mix fab typically rises sharply as the utilization of bottleneck tools increases. (See Figure 1.)

As the fab’s capacity buffer shrinks, variability in tool performance directly affects overall throughput. Conversely, improvements in equipment uptime and other factors can substantially increase throughput, even when the manufacturer does not invest in additional tools.

The fab output, in other words, is not a fixed capacity, but depends on the answers to detailed questions about the constraint tools: What is the throughput of the nitride deposition process? Is the low-k dielectric process module achieving the uptime it should? How does this tool’s unscheduled downtime compare to that of other similar tools, from tool to tool and at other fabs?

It’s difficult for a single fab manager to answer such questions. The best known methods for a process or a maintenance procedure are constantly evolving. Attunement and staff turnover can undermine a fab’s in-house expertise. When tough economic conditions limit hiring, user conferences and service bulletins easily slip to the bottom of an overloaded priority list. Even given sufficient time and other resources, engineers at a single fab simply don’t have the network to tap into the latest best known methods for their tools.

Companies with multiple fabs can compare performance across locations—that’s one reason for “copy exact” methodologies. But even they will only see how their tools behave using their company’s processes and procedures.

A procedure that’s “good enough”—but not ideal—could be replicated across a company’s entire tool base.

AUDITS AND BENCHMARKS ARE THE GOALPOSTS

The Applied Global Services (AGS) FabVantage Group is a consulting team that helps fab managers ensure their tools are achieving optimal performance. While the group does recommend tool upgrades when warranted, substantial improvements can often be made using existing tools and process recipes. A FabVantage engagement typically begins by auditing the fab’s current manufacturing procedures, and benchmarking tool performance against the overall Applied Materials installed base for each tool. Often these first steps identify areas where small procedural changes can bring immediate and substantial benefits.

For example, benchmarking at one Applied customer site showed that their Applied Producer CVD tools were performing below the best-in-class standard achieved at other fabs running similar processes. Unscheduled downtime approached four times the average (Figure 2) and mean time between preventive maintenance (PM) routines was below the benchmark for some applications. The fab’s overall output was suffering, and fab management was unable to predict net output because of high monthly variation in unscheduled downtime.

An equipment audit was performed to verify that best known methods were being followed and that the system settings were optimal. The FabVantage team also evaluated whether scheduled maintenance was being done properly and at the correct intervals. One of the first findings was that the chamber cleaning and conditioning routines were incorrectly configured, causing the cleaning routine to run more frequently than necessary. The excess cleaning cycles were interrupting batches of wafers in process, and were not synchronized with idle time for wafer loading and unloading. Consequently, each cleaning cycle took the system offline longer than necessary. Not only did excess cleaning reduce overall system throughput, it also led to additional wear of the chamber components and hence higher COC and frequency of PM in addition to degraded system reliability and higher unscheduled downtime.

How many chips does a fab produce? It’s a critical question, because the answer affects revenue projections, customer delivery planning, and future expansion plans. Yet it can also be a very difficult question to answer. The throughput and uptime of any of the hundreds of tools in a fab, among other factors, can be ultimately crucial in determining the output of a fab.
The effect of the misconfiguration was aggravated by back-office issues affecting the fab’s operations: spare parts and qualified engineers were often not immediately available, and therefore tools tended to stay down longer than necessary. Fortunately, once these kinds of issues are identified, they are relatively easy to fix. Changing the cleaning strategy and timing—with no change to either the cleaning routine itself or the process recipe—gave an immediate 10-15% improvement in system output. Figure 3 shows the total impact on output which would be obtained by bringing this toolset up to benchmark levels through a combination of improved setup, maintenance and upgrades.

**Modeling and Simulation Support Strategic Experiments While Minimizing Costs**

Modeling and simulation are invaluable tools, allowing fab managers to compare the potential risks and rewards of different strategies without running actual wafers. In this example using our simulation software (Figure 4), tool-level analysis predicted the impact of changes in cleaning strategy before the changes were implemented in the actual fab. At the work-cell level of up to 10 tools, simulation indicated how many wafers can be processed in different configurations. For example, total tool output is usually maximized when all of the chambers of a given mainframe run the same process. This customer had implemented an integrated process configuration in which each chamber is responsible for one step in a complex film stack—an approach that seems intuitively appealing but turns out to be less efficient when tested in simulation. In an integrated process configuration, mismatched processing times for different chambers on the same mainframe result in throughput losses if one chamber needs to wait for loading or unloading because its processing time does not synchronize with other chambers on the system. Alternatively, the maintenance intervals for each chamber may differ, resulting in the system being taken down more frequently. Simulations showed the FabVantage team which investments and changes in the customer’s fab would be most cost-effective. When such clear opportunities for improvement exist, gains can be realized in as little as 6-12 weeks. Over the longer term, changes in fab dispatching strategies and chamber configurations can further enhance the fab’s output.

Using tool simulation, the project team was also able to validate the long-term effects of adopting different software strategies. Previously the customer was not convinced of the benefits of implementing different software options because of negative experiences during actual production. These negative experiences were caused by the complexity of the manufacturing line and the number of different products and recipes. When the customer tested software options, the benefits were often lost in the variability of tools, lots and processes. To work around this, FabVantage experts used actual lot arrival data, reflecting the complexity of the production line, and ran long-term simulations with and without the software options. By using different input conditions and simulating long-term performance, the benefits of implementing different software options were successfully demonstrated to the customer.

In summary, simulations identified significant throughput improvements. An action plan was agreed with the customer to introduce these changes over time. Priority changes were scheduled according to their predicted impact. (See Figure 5.) To date, several system and sequence setting changes have indeed increased throughput by 10-20% across a number of applications. Furthermore it was noted that simulations were valuable for the ideas they quashed as well as the suggestions they validated. A failed experiment in actual production means lost output, if only due to the additional wafers that might have been processed by a more optimal strategy. In a simulation, a failed experiment only costs computer time. In this project challenge, the customer increased output by not only increasing the throughput of the constraint tools, but by addressing the causes of high and variable unscheduled downtime.

By taking an iterative approach, in partnership with the customer, the AG FabVantage Group fine-tuned simulations, minimized disturbance to the manufacturing line, and accelerated the customer’s learning cycle using simulated time.

As the team made actual changes on the tools, measured results, and closed the loop between simulated and actual performance, the precision of the tool models also improved dramatically, prompting the customer to implement additional changes based on positive results and recommendations derived from simulations. Overall fab output is fundamental to every capital spending or revenue model, and it is driven to a large extent by the predictable behavior of individual tools. Tool performance, in turn, rests on a vast array of individual optimizations, from cleaning strategies to system configuration to wafer dispatching logic. A good starting point is to understand how a customer’s tool performance and fab operations compare to the world’s best-in-class facilities. Armed with benchmark results, fab managers can then compare their own procedures to best known methods, and often make substantial performance improvements with little or no additional investment.

Applied Materials’ FabVantage Group helps customers with benchmarking and procedure audits, and supports improved tool performance through process support, equipment optimization, simulation, and other services.

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PROGNOSTIC AND HEALTH MANAGEMENT TOOLS FOR SEMICONDUCTOR MANUFACTURING PREDICTABILITY

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To remain competitive and profitable, semiconductor manufacturers must adhere to the principles of lean manufacturing, just as in any other demand-driven supply chain. This means they need to improve overall company cost and productivity by identifying, and eventually eliminating, activities that don’t add value.

The shop floor presents many opportunities to reduce waste, especially when it comes to operations and maintenance (O&M) of equipment. Currently, frequent calibration and preventive maintenance (PM) schedules ensure high equipment availability and reliability. (See Figure 1a.) However, semiconductor manufacturers face a constantly changing landscape of devices when responding to customer needs, as well as fierce competition brought about by the consolidation of semiconductor players.

In addition, the proliferation of semiconductor-based consumer products and commoditization of technology have driven manufacturing costs down, which in turn drives companies to lower the cost of ownership of their production assets. As the PM cost curve in Figure 1b indicates, reducing unproductive planned PM cycles can reduce operating expenses—but it also increases the risk of much more expensive unplanned downtime due to equipment failure.

The risk increases because manufacturers cannot accurately determine the actual condition of their equipment. Clearly, there is a need for performance estimation and prediction capabilities that will provide:

- **Efficiency improvements**
  - Reduction in unscheduled downtime, increase equipment uptime and availability, decrease in MTBF, troubleshooting time and MTTR
- **Cost reductions**
  - Consumables can be more efficiently used, reduction in test wafer usage, improvement in inventory control
- **Quality improvements**
  - Reduce tool variability, minimize rework and scraps, etc.

![Figure 1. PM cost vs (a) availability and (b) PM interval.](image)
PROGNOSTIC AND HEALTH MANAGEMENT TOOLS
FOR SEMICONDUCTOR MANUFACTURING PREDICTABILITY

PROGNOSTICS & HEALTH MANAGEMENT (PHM)

PHM applies a maintenance paradigm (reactive, preventive, condition-based maintenance (CBM) and predictive) to a particular equipment monitoring task when and where it is appropriate.

- Reactive maintenance can be used when performing quick replacement/repair of noncritical components that do not adversely affect part quality and production throughput.
- Preventive maintenance is applied to critical equipment subsystems and parts where sudden or hard fault events are known to occur or when there isn’t sufficient knowledge of their degradation or failure modes.
- Predictive approaches should be used when reliable models for part degradation and a reasonable horizon window for performing maintenance are available.

- CBM is helpful in situations when equipment drift indicators can be tracked but no repeatable models can be established. Repairs are done when the indicators exceed a predefined threshold that was set using historical maintenance events.
- Preventive maintenance is applied to critical equipment subsystems and parts where sudden or hard fault events are known to occur or when there isn’t sufficient knowledge of their degradation or failure modes.
- Machine-learning tools and algorithms are used to implement a PHM program by applying mathematical models to equipment and factory data to first infer tool failure events, and then act on those prediction results to improve factory productivity. PHM tools for signal processing and feature extraction can assess and predict performance based on input from sensors, historical data and operating conditions. These PHM techniques transform input data into a set of features such as health assessment, performance prediction and fault diagnosis. The Center for Intelligent Maintenance Systems (IMS) has established a systematic instrumentation approach (see Figure 2) that uses PHM tools and algorithms to develop predictive technologies for critical equipment and components. Once data is collected from a monitored asset, filtering and signal processing tools are applied to remove outliers, transform data into another domain and extract features or health indicators. Because a large set of health indicators is typically produced, a reduction/selection method should be adopted to ensure fast convergence and accurate equipment health models. Health assessment tools use relevant health indicators to estimate degradation or performance. The health metric, also known as confidence value or CV, is an objective estimate of equipment performance that can be correlated to maintenance activities. CV can also be developed to provide health metrics at the subsystem, module, component or consumable levels. This is extremely useful in helping maintenance staff troubleshoot faster and more accurately.

It is computed by a statistical comparison of current health indicators with a known baseline condition. Prediction algorithms can infer equipment performance in future machine cycles. Diagnosis methods can provide insights into which component is most likely to fail and the type of failure mode that will occur. Finally, visualization tools can be employed to deliver the right health information (current health degradation, remaining useful life, fault mode, component at fault, etc.) to the right person (equipment manager, operator, production supervisor, manufacturing and process engineers, etc.).

LESSONS LEARNED FROM OTHER INDUSTRIES

PHM has been widely used in other industries for various purposes. In machine tools, for example, predictive algorithms help users monitor the condition of cutting tools to extend tool life and avoid conditions detrimental to surface quality, thereby reducing rework and scrap. In the aviation industry, safety is the primary driver for using PHM tools to monitor engines and aircraft equipment, thus avoiding catastrophic failures. Automotive manufacturers employ PHM programs for their industrial robots to ensure uninterrupted production and assembly, because downtime events are prohibitively expensive. Military applications employ integrated vehicle health management (IVHM) as a decision support tool to evaluate mission readiness of fighter planes and all-terrain vehicles before field deployment.

The widespread use of PHM in other industries came after decades of research and development in order to overcome major challenges such as insufficient instrumentation, data, storage, processing power, etc. Today the advancement of sensing and data acquisition techniques, coupled with the emergence of powerful processors and the discovery of numerous analytic tools and algorithms, has mitigated many of these implementation challenges. However, manufacturers in the semiconductor and other segments are then confronted with the monumental task of melding a PHM framework that leverages these advanced technologies to address their industry-specific issues.

CURRENT STATE OF PHM IN THE SEMICONDUCTOR INDUSTRY

Most semiconductor device manufacturers already use advanced techniques such as statistical process control (SPC), measurement system analysis (MSA), and fault detection and classification (FDC) to analyze process control, sensor and metrology data to perform run-to-run (R2R) control and advanced process control (APC). Independently, original equipment manufacturers (OEMs) have made huge strides in advancing the sensing technology in their products and developing custom equipment diagnostics. Some OEMs have started developing high-level equipment state estimators, but these are not yet available. Despite these PHM advances, time- and usage-based replacement of components and consumables is still widely practiced. Most existing semiconductor manufacturing equipment does not incorporate advanced analytic and predictive capabilities to determine future condition. It also does not provide drill-down functionality to determine which subsystem or component/consumable is degrading and will eventually require conditioning or replacement.

To effectively implement PHM in the semiconductor manufacturing industry, both the semiconductor device manufacturer and the OEM must collaborate to support PHM capability. Requirements include:

- Creating implementation guidelines and architectures.
- Developing data standards and working together (or with a third-party integrator) to validate and obtain proven predictive algorithms and mathematical models.
- Agreeing on IP concerns about data sharing and ownership, and commercialization and implementation paths (for example, dealing with custom factory framework and architecture).

The most recent initiatives in this regard have been the completion of two PHM pilot projects, sponsored by the International Sematech Manufacturing Initiative (ISMII), each involving real production data from two different semiconductor device manufacturers on two tools from two different OEMs and two different universities. In...
PROGNOSTIC AND HEALTH MANAGEMENT TOOLS
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MOVING TOWARD EQUIPMENT PREDICTABILITY

Once semiconductor device manufacturers and OEMs begin this mutually beneficial collaboration, the next few years will see a surge in research that will lead to transparency of equipment performance and ultimately result in the “Factory of Tomorrow” as illustrated in Figure 3. The modern semiconductor production floor, equipped with an IT infrastructure that may include MES and ERP systems, provides a setting where data can be aggregated from inline metrology measurements, wafer trace data, process controller data and even sensor signals from select auxiliary equipment components. PHM tools can then combine the collected data, process knowledge (equipment usage patterns, maintenance history and effect of faults on the system), and component design knowledge (failure modes, lifetime expectancies and wear profiles) into a predictive health metric that can be visualized using degradation curves, multi-component radar charts, fault maps and risk charts.

Semiconductor device manufacturers can use this health metric to develop virtual metrology for more accurate yield prediction, enhance existing APC, improve R2R to incorporate equipment drift, and finally achieve optimal production and maintenance scheduling (just-in-time manufacturing). At the enterprise level, the health metric can be used to objectively compute a factory-wide overall equipment effectiveness (OEE) index based on the true condition of the equipment. Finally, historical health information can provide valuable feedback to both semiconductor device manufacturers (process design and efficiency improvements) and OEMs (equipment redesign and upgrades).

BENEFITS OF PHM

PHM will enable significant improvements in cost reduction, operation efficiency and product quality for semiconductor device manufacturers.

- Cost Reduction
  With a properly implemented PHM program, factory managers can exercise just-in-time maintenance that makes more efficient use of equipment repair labor. Because the equipment’s useful life can be extended (thereby extending PM intervals), consumable and component utilization are maximized. A reduction in tool-induced excursions and test wafer usage can also be expected.

- Operation Efficiency
  A health metric that describes equipment (subsystem/module/ component) performance or degradation can be used to maximize equipment availability and uptime, and increase net WIP output. With prediction and diagnosis capabilities, mean time between failures (MTBF), troubleshooting time, and repair time (MTTR) and unplanned downtime can all be curtailed.

- Product Quality Improvement
  Process engineers can include equipment variability and drift to enhance their R2R and APC systems so that product quality deviations are minimized (including rework, scrap and excursions). It is to the equipment supplier’s advantage to “design in” advanced PHM capabilities in order to convert advanced design knowledge of their product into increased equipment value, differentiate their product from competitors’ offerings, and achieve greater customer satisfaction.

PHM IMPLEMENTATION CHALLENGES IN THE SEMICONDUCTOR MANUFACTURING INDUSTRY

The semiconductor manufacturing industry can leverage decades of experience from other industries in developing its own PHM applications. However, this manufacturing sector is faced with some unique implementation challenges:

- Equipment can be a source of multiple signals and features but most are either redundant or not useful (importance of feature selection).
- Robust models that can handle chamber-to-chamber variation (work across multiple chambers) must be developed because variations make it more difficult to set thresholds for health indicators or feature values. Moreover, variations can cause different degradation rates and health condition baselines.
- The effects of process (variety and complexity of recipe, usage, etc.) on equipment degradation must be understood.

- Validation and refinement of health monitoring and predictive algorithms require more field data and potentially longer PM intervals to determine what a true unacceptable health value is and what additional equipment life is not being used.

- Health results must be integrated with asset management and production systems (FDC, R2R, APC, etc.), because ultimately the information will be used to increase yield and reduce maintenance costs and downtime.

Applied Materials recently joined the IMS consortium to help establish research collaboration protocols to address these challenges. Applied Materials plans to use PHM analytic tools to incorporate predictive technologies into its offerings so that customers can reduce costs, operate more efficiently and improve product quality.

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Feature selection follows an exhaustive feature extraction by choosing a smaller subset of significant and relevant health indicators for developing learning models. With an optimized set of health indicators, a PHM system can take advantage of faster model convergence, better model interpretability, more comprehensive generalization of the original sensor measurements and finally tractability.

Support Vector Machine (SVM) is a supervised learning method that can be used for classification and regression analysis. It generally involves a training phase that requires health indicators with the corresponding label or equipment condition (good or bad/faulty). The objective of using SVM is to use the trained model to predict equipment condition given only the current health condition.

Asymmetric Vector Machine (ASVM) is a variant of the basic SVM that introduces a bias towards one class/condition.

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Since its inception in 2001, the National Science Foundation’s Industry & University Cooperative Research Center (NSF-I/UCRC) for Intelligent Maintenance Systems (IMS) has been focused on enabling products and systems with performance prediction capabilities. The IMS Center is a multi-campus NSF Center of Excellence with research sites at the University of Cincinnati (lead institution), the University of Michigan and the Missouri University of Science & Technology. The IMS Center has collaborated with more than 70 global companies and conducted more than 100 projects for research validation.

The Watchdog Agent is a toolbox of algorithms developed by the IMS Center to transform machine, process and maintenance data into equipment health indicators. For more information about the IMS Center and its research, please visit www.imscenter.net or contact Prof. Jay Lee, Center Director, at jay.lee@uc.edu.

The IMS Center implemented a multivariate data-driven surge map modeling approach that adapts to ambient conditions to predict and prevent surge events. The overall approach is shown in Figure 5. Various sensors were installed on the test-bed to record variables during air compressor operation and capture ambient conditions such as humidity and temperature. Surge tests were performed over a certain duration to sample different operating scenarios. Principal component analysis (PCA) or PCA was then reduced to use the number of health indicators to maximize model complexity.

The IMS Center used an algorithm called support vector machines (SVM) to find the surge surface that maximizes the distance between surge and non-surge conditions. Basically, SVM is a supervised machine-learning method used to analyze data and recognize patterns. The SVM algorithm was further improved by using a variant of the method, asymmetric support vector machines (ASVM) to minimize unpredicted surge occurrences.

The IMS PHM solution

The IMS Center developed a systematic methodology of data-driven surge map modeling using PHM tools and algorithms, their approach was validated with surge test data from the compressor test-bed. With help from the compressor OEM, Toyota retrofitted the existing compressor units with the surge detection module into the CAS controller system.

As a result of this collaboration, CAS reliability greatly improved at the Toyota facility. Associated maintenance costs and production loss were also reduced. The addition of pressure control improved CAS efficiency. An internal facility audit revealed an annual energy savings of around $50K. The once centrifugal compressor surge prediction technology was installed.

Figure 4. Centrifugal compressor surge map.

Figure 5. Data-driven surge map modeling approach for centrifugal compressors.
ADVANCED, PREDICTIVE SCHEDULING TECHNOLOGY
CAN IMPROVE LITHO CELL PRODUCTIVITY

In less than two decades, fab operations have moved from semi-automated to highly automated, and now, to interconnected mega fabs, with complexity that pushes the boundaries of the most advanced state of the art. These mega fabs, which are designed to process hundreds of thousands of wafers monthly, are being built in Japan, South Korea, Taiwan and the United States, and rely on both real-time dispatching technology and optimized production schedules to reach their potential production capability.

The state of the art in most fabs today involves the use of real-time dispatching rules that select lots only from on-hand work in process (WIP) at the moment a tool becomes available. Some very sophisticated RTD rules do look ahead in an effort to predict the arrival of lots. However, this limited look-ahead capability is usually confined to batch formation in the wet processing and diffusion areas. In most circumstances, the look-ahead capabilities are limited to looking upstream in the process flow a few steps. However, these solutions do not scale to meet the complex needs of interconnected mega fabs.

Applied’s SmartSched advances the state of the art in semiconductor fab operations, adding very accurate WIP prediction and schedule optimization to the capabilities of the company’s fab operation management technologies. Together, SmartSched and Applied Real-Time Dispatcher (RTD) define the new state of the art, and set a de facto standard for mega fab operations.

SmartSched is the semiconductor industry’s only commercially available predictive scheduling software. It functions by constantly looking ahead in time to predict the arrival of lots so that the system can optimize the production schedule for critical tool groups. SmartSched feeds predicted lot arrivals to a scheduler that evaluates millions of “what-if” scenarios against fab objectives. By considering fab transfers, different tool assignments and processing sequences, it predicts the outcome of each scenario and develops a short-interval manufacturing schedule. Its direct connection with RTD enables the dispatcher to immediately execute the optimized schedule. This is the new state of the art.

CASE STUDIES
1. SmartSched Optimization for Photolithography

Toshiba’s efforts to maximize litho cell output reflect their understanding of the potential of schedule optimization to improve lithography operations. In a recent news release, Masanori Morikawa, senior manager of manufacturing engineering at the Toshiba Yokkaichi Operations, currently one of the world’s largest 300mm mega fabs, said, “Unlocking litho capacity was identified as a critical step in increasing output in our manufacturing operations. We selected Applied’s SmartSched solution because it offers the quickest, most-cost-effective route to optimize throughput and reduce cycle time, focusing first on lithography steps. We plan on working with Applied to extend SmartSched capability to meet additional Toshiba production requirements so we can improve output and equipment utilization in multiple areas of our manufacturing operations.”

In most fabs around the world, photolithography is a bottleneck area. In an advanced fab, the high equipment and reticle costs and an increasing number of device layers can account for about a third of the cost of manufacturing a semiconductor chip. Thus, companies have spent many years developing systems that seek to optimize lithography operations as much as possible.

The key to optimizing photolithography and other bottleneck areas is to return to fundamentals. In photolithography this means reducing the number of temperature change delays on the coat and developer tracks (track systems are very sensitive to temperature change), minimizing reticle changes, managing active advanced process control (APC) threads, and minimizing the impact of send-ahead lots. (See Figure 1.)

Faced with the problem of either buying additional litho tools (at ~$45 million per system) to increase output and reduce cycle time, or finding a way to more effectively leverage current investments, chipmakers are choosing to leverage optimized scheduling technology, like SmartSched, to improve litho tool utilization.

The upper graph in Figure 2 shows reticle changes in a 12-hour shift using only real-time dispatching rules. These dispatching rules choose the best lot to process from the available queue each time a load-port becomes available. If we were to zoom in on this schedule, we would see small amounts of idle tool time each time a reticle change is needed and each time there is a significant setup change on the coat track. This idle time, often called “bad whitespace,” is avoidable.

The lower graph in Figure 2 shows how SmartSched uses its predictive capabilities to look ahead and schedule the whole 12-hour shift. The result is a significant reduction in setup changes and reticle changes. The bad whitespace that is almost invisible in the upper schedule is saved by SmartSched and we can see it at the end of the schedule as “good whitespace.” This good whitespace is tool capacity that is now available.

2. Optimizing Reticle Delivery Scheduling

In an early production use of SmartSched, the environment was very different from that described previously. The product mix was much higher and therefore there was less opportunity to make improvements through setup reduction. In this environment the challenge was to better manage the distribution of WIP across the qualified tools and ensure that qualified reticles are delivered where needed to improve tool utilization and throughput.

Figure 3 shows how automating reticle scheduling can overcome previous trends of decreased wafers at certain times of day, and elevate the overall wafer count throughout the 24-hour time period that was tracked. By better predicting reticle usage by each tool, SmartSched published a schedule that allowed operators to ensure that needed reticles were inspected and delivered to each tool just in time.

The optimized schedule for each litho station also resulted in a reduction in send-ahead lots and metrology operations and reduced the cycle time for lots that triggered send-ahead metrology. (See Figure 4.)

The results of this second case study show both more predictable and increased hourly and overall throughput, a reduction in the number of send-ahead lots, an increase in equipment utilization (See Figure 5), and a reduction in utilization variance. SmartSched helped drive a significant improvement in overall lithography operations.

CONCLUSION

Fab operations in the age of the mega fab need to advance the state-of-the-art beyond real-time dispatching alone. Advanced scheduling systems like SmartSched that can look into the future, accurately predict lot movement, and optimize schedules for bottleneck tools are essential and represent the new state of the art. SmartSched’s capability to predict WIP movement and then to create an optimized production schedule reduces otherwise wasted equipment capacity and metrology operations, resulting in significant equipment utilization, throughput, and cycle time improvements.

SmartSched is a key advancement in predictive scheduling, delivering improvement in the most complex areas of semiconductor manufacturing and doing so in the largest and most advanced fabs in the world.

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Figure 1. SmartSched reduces wasted capacity resulting from unnecessary setup and rework.

Figure 2. SmartSched converts bad whitespace to usable equipment capacity.

Figure 3. Hourly throughput improvements resulting from optimized reticle scheduling and delivery.

Figure 4. Reducing send-ahead wafers leads to fewer interrupts and less tool whitespace.

Figure 5. Litho equipment utilization can be significantly improved with SmartSched.
Solar energy has begun to reach the tipping point where photovoltaic electricity can compete with grid power, especially in sunny island areas like Malta and the Caribbean. Installations have exploded: the world’s total installed base was less than 2 GW in 2001, while more than 18 GW of new generating capacity came online in 2010 alone. By the end of 2011, the global installed base is likely to reach 65 GW. This enormous growth has brought tremendous opportunities for solar cell manufacturers, but has also attracted many new competitors to the industry. Volume alone is no longer enough to make a solar fab cost competitive. There are many high volume fabs already, with more under construction. To minimize costs is no longer enough to make a solar fab cost competitive. There are many variables accounting for this growth.

Solar cell yield has three components: mechanical, electrical, and cosmetic yield. A typical fab’s yield loss distribution is shown in Figure 1. While cosmetic yield — mostly attributable to color variations — lies within the control of the fab, mechanical and electrical yield largely depend on the quality of the incoming wafers. In a typical mainstream solar fab, incoming wafers may fall into any of over a dozen classifications covering such properties as silicon purity, crystal quality, dislocation and grain boundary variation, and dopant distribution. Minority carrier lifetimes range from 0.5 to 25 µsec for multicrystalline cells and 100-500 µsec for typical monocrystalline wafers. Typical average efficiency for multicrystalline (multi) cells ranges from 16.5 to 17% while monocrystalline (mono) cells range from 17.5 to 18.2% average efficiency. Even with improved process controls and quality across cell lines, the overall range of performance varies by almost 2.5% for multi cells and 1.5% for mono cells. This range is primarily due to variable wafer quality, particularly minority carrier lifetime.

Indeed, wafer quality variations account for as much as 2/3 of the variance in final cell efficiency. Figure 2 simulates the effect on multi-cell efficiency of lifetime variations from 5-25 µsec, along with variations in process metrics such as reflectance, line-width, and emitter and passivation quality. Even though process optimization can help a fab get the most from its incoming wafers, a wafer with a 1 microsecond carrier lifetime will never achieve the efficiency that a higher quality wafer can unless it is improved by special processing.

Variable raw material quality presents a dilemma for fab owners and process engineers. What are reasonable targets for cell yield and wafer breakage? How successful is a given line optimization likely to be? How many watts can the plant’s output actually generate, and how much revenue can the fab expect? Yield losses due to scrap, breakage and electrical efficiency loss affect the fab’s bottom line. Higher efficiency modules earn a higher price premium, so a tighter cell efficiency distribution is critical. Predictable fab output is fundamental to every revenue projection and capacity planning decision fab owners make, but output forecasts are unreliable unless the fab’s inputs are understood.

In the integrated circuit industry, individual wafers are labeled with serial numbers and tracked from the beginning of the line to the end. Defect inspections along the way establish a yield expectation for each wafer and, over time, for the fab as a whole. This level of tracking is probably not feasible for solar cell fabs. Today’s solar fabs may have thirty to fifty thousand wafers being processed in total every hour, valued at about a dollar each. An integrated circuit fab handles only a few hundred wafers per hour, each worth hundreds or thousands of dollars, depending on the stage of processing.

**WAFER BINNING SETS YIELD EXPECTATIONS**

A more meaningful tracking unit for solar fabs is the batch. Wafers sliced from the same part of a given ingot are likely to have similar properties. At incoming inspection, tools like scanning photoluminescence spectroscopy can rapidly sort wafers based on characteristics like lifetime. Physical defects may be readily classified on the basis of physical and optical detector-based tools. Armed with this information, fabs can more readily predict end-of-line yield and efficiency for each batch.

Binning information, in turn, can drive a wide range of optimizations, from individual tools to company-level strategies. After models of the interrelationship between materials and processes are developed, the fab can use them...
to design appropriate feedback loops and control systems. A fab can use this information to define and identify an “out-of-spec” process, or one that has deviated so far from optimal that it should be taken off-line for repair or recalibration. One example of this approach, developed by Applied Materials, is shown in Figure 3. This figure explains how wafer metrology and binning at the end of a wafering step can improve wafer quality through classification of failures and improvements in the wafering process. Separating incoming wafers by quality level will allow a cell line to produce more predictable results, thus supporting further improvements in each line through process control and new technology. For example, one of the most common causes of breakage is the backside metallization process. The thermal expansion mismatch between aluminum and silicon creates substantial stress. Incoming wafers with micro-cracks or edge flaws are more likely to fail under these conditions. Wafer binner data allows a fab to determine whether an increase in breakage is due to a tool defect or to the arrival of a particularly cracked or flawed wafer. As a selective emitter process, for example, a new process line is being installed, wafer quality data can save weeks of setup and troubleshooting time, helping engineers to determine whether a particular result is due to the wafers or the tools.

**BEETR FORECASTS DRIVE BETTER STRATEGY**

Finally, at the strategic level, a company can begin to analyze the relationship between incoming wafer quality, selling price, and profit. Maybe the higher selling price that high efficiency cells demand justifies the purchase of better quality silicon. Conversely, maybe lower grade silicon should carry an even steeper discount because of its lower yield and efficiency. Though asking these questions seems obvious, answering them depends on good information about both incoming wafers and the capabilities of the process line.

As the solar industry grows and becomes more competitive, fabs need to understand how their operations compare to the world’s best in class facilities. Improved benchmarking and incoming wafer inspection allow them to set realistic fab performance expectations, and to develop appropriate batch level tracking, inline metrology, and process control methodology to make sure that tighter performance goals are met across each level from wafering to cell and module manufacturing. Solar lines with improved process control, metrology and automation can save 3-5 cents/watt of overall cost through improved yields, better efficiency distribution and reduced scrap.

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MANAGE VOLATILITY:
TRANSFORM SERVICE INTO A VARIABLE COST

BY KERWIN HOVERSTEN

Applied’s offerings flex with market changes to emphasize uptime or throughput.

Wherever possible semiconductor manufacturers want to quickly transform fixed costs into variable costs that scale with production, enabling them to meet fluctuating market demand predictably and profitably.

Both the new Applied Adaptive Service and the more traditional Applied Performance Service provide the flexibility and comprehensive support needed to do this. Each enhances the productivity and profitability of fab operations at low, predictable costs that scale with fab loading.

These services can incorporate market-leading Applied E3 automation software, a fab-wide automation and equipment engineering solution that enables fabs to run more efficiently and at a lower total cost of operation. E3 provides Applied’s service experts with onboard tool-monitoring data, giving them a more complete understanding of tool performance and helping them avoid or better respond to variation and excursions.

Although each service has fixed and variable cost components, there are important distinctions. Applied Adaptive Service is a new offering designed for customers with highly variable production levels. It features a completely flexible cost structure that provides the opportunity to completely align service costs with the customer’s run rate. In essence, it guarantees the tool uptime needed to meet specified fab loading levels.

With Adaptive Service, Applied commits to meet throughput requirements and both the fixed and variable cost components flex in line with the fab utilization rate.

Both can be adjusted as often as quarterly, based on the run rate. The variable component is built on per-tool service pricing based on tool-specific critical parameters (e.g., hours of RF operation, number of wafers processed, etc.).

For example, a high-mix, high-change production environment where tool utilization rates vary greatly, such as a foundry with new, state-of-the-art 300mm production capabilities that are not yet fully utilized, will benefit greatly from this cost flexibility.

Applied Performance Service, meanwhile, guarantees tool uptime regardless of the run rate. Its cost structure is based on a fixed amount that doesn’t change, plus a variable cost adder aligned to tool-specific critical parameters. Customers can realize additional cost flexibility by idling unneeded tools, up to a certain percentage, when fab loading levels are lower.

Applied Performance Service can be implemented in many different ways. For example, one fab with 42 tools (PVD, etch, DCVD and FEP) had been using a mix of Applied and in-house maintenance. Fab management switched all their Applied Materials tools to Applied Performance Service and, as part of the package, the E3 automation software was installed on the entire installed base of tools. At the time, the customer had been experiencing some puzzling, erratic behaviors with their PVD tools. With E3, the root cause of the inconsistent performance was quickly identified and fixed. In the end, the customer achieved performance improvements of up to 12% on critical PVD applications, with related cost reductions of more than 10%.

Another customer with 64 tools (implant, etch, DCVD, etc.) implemented Applied Performance Service, including E3 automation and Applied’s ExpertConnect remote diagnostic capability. The technology enabled predictive maintenance models to be developed that helped identify potential trends and problems before they resulted in yield-killing issues. The service ultimately delivered fixed cost reductions of 15% and variable cost reductions of 10%, and allowed the customer to achieve leaner manufacturing status.

With the highly cyclical nature and intense cost pressure of the semiconductor industry, the complexity of balancing output and costs is greater than ever. New service programs like these, aided by E3 and ExpertConnect, and an ever-growing roster of technical innovations, are helping chipmakers adjust costs to market and fab conditions and identify problems sooner—or before they happen at all.

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FROM “FAIL AND FIX” TO “PREDICT AND PREVENT”:

IMPROVING FACTORY ROI WITH PROGNOSTICS AND HEALTH MANAGEMENT

BY MICHAEL ARMACOST AND TONY MARTINEZ

Following the successful example of suppliers in other industries, Applied Materials is moving toward a prognostics and health management (PHM) model for equipment maintenance that will enable this more proactive approach. Working collaboratively with the Center for Intelligent Maintenance Systems (CIMS) (see related article on page 100), the company is developing an integrated suite of tools and services to ultimately enable manufacturers to adopt predictive strategies that help them operate tools and fabs more efficiently, with lower costs and higher output.

WHAT IS PHM?

Based on in-depth characterization and modeling, PHM methodologies are designed to predict future tool performance by assessing its deviation and/or degradation from a normal, “healthy” operating condition. PHM methodologies reduce unscheduled events and total downtime to increase equipment efficiency. Shorter MTBC and MTTR, and reduced maintenance costs through more accurate diagnostics are added benefits. Additionally, higher tool reliability minimizes rework and scrap and uses fewer test wafers, resulting in lower costs. Further, reducing unscheduled downs improves the WIP predictability for more accurate dispatching decisions.

TRANSFORMING DATA INTO ACTION

At the center of the PHM approach is Applied E3 data acquisition software, which enables the collection and transformation of tool data into information that can be used to make, and eventually, predict key decisions about equipment maintenance actions and scheduling. Figure 1 This data is a combination of status variable identification (SVID) data, specific sensor output, on-wafer results, or perhaps a virtual identifier that is a combination of several of these. The implementation of PHM is best thought of in several levels.

EXCERSION CONTROL

Exciursion control is a system that tracks performance violations against preset limits and alerts the user when these limits are violated. The purpose is to provide an early warning mechanism to minimize the damage and waste once an excursion has occurred. Excursion control is implemented on individual tools and across the tool set in the fab. Controlling equipment and process excursions involves extensive data collection and monitoring for any deviations associated with this data. At the first level, statistical limits are derived from all tools running a standard process with the same hardware configuration. In this case, statistical limits are typically large, since the chambers can be in a variety of states at any time. At the tool level, single-chamber variations are much tighter, and must account for drifts associated with changing process conditions.

PHM generally involves the following:

- Identifying key failure modes for a particular piece of equipment or a related subsystem. For example, models that predict RF mismatch failures or end-of-use life of certain consumable parts.
- Analyzing a set of interrelated tool outputs to create a virtual signal that indicates tool or component degradation or imminent failure.
- Testing the model in a production environment to ensure that it correctly forecasts a component problem.
- Predictive maintenance (PdM) requires identification of specific tool problems that can feasibly be modeled and predicted. Once a problem has been identified, there must be enough flexibility in the software to combine different subsystems to model the pertinent events.

The next higher level of sophistication is predictive maintenance (PdM) in which methods/algorithms are developed that characterize complex tool problems to provide prediction of likely problems before they actually occur. The goal of PdM is to prevent unplanned downtime, enabling potential problems to be addressed during a scheduled routine maintenance. This minimizes the excessive time and cost devoted to an unplanned down including the wafer loss associated with failures.

Excursion control can be applied to any tool output—both on the tool itself or on-on-wafer results. The challenge in implementing excursion control is in identifying the right variables/signals to track. Many times, meaningful deviations of system parameters are subtle and not easy to detect.

The limitation of excursion control is that the alert happens only after the problem has occurred. Limits can be set very low to provide early warning before damage is done, however, this has the downside of frequent interruption—and associated downtime. Looser limits reduce the number of interventions but increase the risk that each excursion is catastrophic.

PREDICTIVE MAINTENANCE

The next higher level of sophistication is predictive maintenance (PdM) in which methods/algorithms are developed that characterize complex tool problems to provide prediction of likely problems before they actually occur. The goal of PdM is to prevent unplanned downtime, enabling potential problems to be addressed during a scheduled routine maintenance. This minimizes the excessive time and cost devoted to an unplanned down including the wafer loss associated with failures.

PdM generally involves the following:

- Predictive maintenance models a piece of equipment or a related subsystem, e.g., components that are monitored or the fab environment that is monitored.
- Predictive maintenance provides early warning to enable attendance to a specific equipment problem before it turns into a failure.

Figure 1: Data is of little value without the ability to translate it into actionable information.
FROM “FAIL AND FIX” TO “PREDICT AND PREVENT”: IMPROVING FACTORY ROI WITH PROGNOSTICS AND HEALTH MANAGEMENT

can be installed to alert the user to check the Pirani gauge port when the pressure reaches a preset level, thus triggering a service routine before there is any subsequent process impact. Unfortunately, the complexity of semiconductor process tools is such that most failures are not easily tracked and monitored. Models must be based on tracking many pieces of operational data, and then using sophisticated mining technologies to identify variables, or more often combinations of variables, that can be associated with a given failure mode. Eventually a virtual sensor is identified and a model is built on sensor performance under various failure/ deterioration conditions. A typical example is highlighted by monitoring wafer lift speeds to prevent helium leak faults. Helium leak faults can be catastrophic to wafer yield, since uncontrolled substrate temperature can lead to process fluctuations. One cause of such leaks has been linked to the speed of the electrostatic chuck wafer lift. If the wafer stayed too quickly, there will be insufficient time for proper chucking to occur, resulting in leakage of helium used to cool the wafer. Measurement of this parameter is not trivial, as this it occurs after the wafer has stopped standard processing, and the digital signal of the lift actuator does not provide sufficient data to determine subtle variances in system setup. The complexity of this measurement is highlighted in Figure 3. Initially a trigger point is selected, such as the ESC helium valve closure (a). From this point, the lift actuator digital signal indicating lift initiation is identified (b). When this occurs, the flow through the foreline pressure is monitored (c.). When the lift actuator I/O indicates the pins are fully up (d.), then the foreline pressure signal is terminated (e.), and the length of the flow duration through the lift is calculated.

This technique enables measurement of the lift pin speed with sufficient granularity to determine differences within chambers which could cause helium leakage issues. Figure 4 is an example of three chambers which were monitored for this issue. In this instance, Chamber A was showing signs of sporadic behavior where the lift pins speed was significantly faster than the fleet. After the lift speed was adjusted, the leak was eliminated.

PIHM is advancing rapidly from development to real-world lab applications, with multiple PIHM strategies currently in beta test by Applied customers. These packages address a variety of unscheduled down-time failure modes related to a particular chamber or tool. PIHM strategies for the following tool sets are currently being tested:

- CMP - Reflection LK and GT
- Etch - AdvanceEdge, Enabler
- CVD – PE Silane and Producer SACVD
- PVD - Endura AI

Figure 2: Predictive model of the foreline pressure behavior. Gradual increase in the pressure was caused by a contaminated Pirani gauge.

Figure 3: Schematic describing signal timing for evaluating the lift pin speed in a typical vacuum process chamber.

The next level of sophistication in tool maintenance is the development of a comprehensive equipment health index. A health index takes into account all the various health indicators (virtual and real) and, based on empirical and artificial intelligence, assigns a weighting to each indicator and combines this with the degree of variation of these from normal (healthy) operation. The result is a single composite health index. Once critical deviations have been identified, it’s important to examine how they interact in order to determine which parameters are out of spec, to what degree they are out of spec, and what the combinations of these parameters for the subsystem or component that is not working properly. The interactions can be linked together using statistical, engineering and first principles. In Figure 5, the y-axis indicates a relative value of the degree of deviation for all the monitored parameters for this process. Each subgroup on the bar represents a generic subsystem, such as the RF subsystem, which includes all match and generator parameters, or a flow system that includes all flow controllers, FDC and throttle valve sensors. By summarizing the data in this manner, a technician can quickly identify that over the period of time analyzed, chamber B has an issue that needs to be addressed.

An equipment health index is flexible, and can use a variety of statistical approaches to determine which chambers or recipes need to be examined, and which are not healthy. Eventually, these approaches will be linked to various logic sequences to determine which components are linked to a signature of shifts, thereby identifying which chambers should be examined first.

Applied Materials expects to apply equipment health indices on both 200mm and 300mm top-priority tools and eventually link this health information with wafer information. Future applications will include a tool health user GUI and will eventually enable the integration of tool health conditions with RF dispatch and processing.

Figure 4: Lift speed versus date for several chambers for a conductor etch chamber. Lift pin deviations in Chamber A were identified and corrected to eliminate the possibility of He backside faults.

SUCCESS METRICS

Although the PIHM features described in this article reflect the breadth of Applied’s engineering and software capabilities, they are really just a means to an end. PIHM features are designed to improve overall tool performance at customer fabs. Key tool-level success metrics are:

- Increased tool availability
- Reduced MTTR
- Extended Mean Time Between Cleans (MTBC)
- Increased wafer outs
- Extended life of consumables
- Improved on-wafer quality

Current metrics are being tracked at key customer sites in order to determine what impact PIHM-enabled tools have in a production environment.

CONCLUSION

Many semiconductor manufacturers recognize the economic value to be gained from improved equipment performance—especially equipment maintenance. By using the new PIHM-enabled tools now in development, manufacturers can begin to migrate from an inefficient “fail and fix” paradigm to a much more cost-effective “predict and prevent” approach that can significantly improve factory ROI.

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Definitions:

- Prognostics is an engineering discipline focused on predicting the time at which a system or a component will no longer perform its intended function.
- PIHM is an e-signature of a component by assessing the extent of deviation or degradation of a system from its expected normal operating conditions. The science of prognostics is based on the analysis of failure modes, detection of early signs of wear and aging, and fault conditions. These signs are then correlated with a damage propagation model. Potential uses for prosthetics include condition-based maintenance.

The discipline that links studies of failure mechanisms to system lifecycle management is often referred to as prognostics and health management (PMH), sometimes also system health management (SHM) or—in transportation applications—vehicle health management (VHM). Technical approaches to building models in prognostics can be categorized broadly into data-driven approaches, model-based approaches, and hybrid approaches. As the name implies, data-driven techniques utilize monitored operational data related to system health. Data-driven approaches are appropriate when the understanding of first principles of system operation is not comprehensive or when the system is sufficiently complex that developing an accurate model is prohibitively expensive. Therefore, principal advantages to data-driven approaches is that they can often be deployed faster and more cheaply than other approaches, and that they can provide system-wide coverage (cf. physics-based models, which can be quite narrow in scope). The principal disadvantage is that data-driven approaches may have wider confidence intervals than other approaches and that they require a substantial amount of data for training. Data-driven approaches can be further subcategorized into: data-driven models and sensor-based conditioning. In addition, data-driven techniques also subsume cycle-counting techniques that may include domain knowledge. The two basic data-driven strategies involves (1) modeling cumulative damage (or equivalently, health) and then extrapolating out to a damage (or health) threshold, or (2) learning directly from data the remaining useful life.

As mentioned, a principal bottleneck in obtaining run-to-failure data, in particular for new systems, since running systems to failure can be a lengthy and rather costly process. Even where data exist, the efficacy of data-driven approaches is not only dependent on the quantity but also on the quality of system operational data. These data sources may include temperature, pressure, oil debris, currents, voltages, power, vibration and acoustic signal, spectrometric data as well as calibration and calorimetric data. Features must be extracted from (more often than not) noisy, high-dimensional data.
A Customer Story

WHEN DISASTER HAPPENS
A STORY OF RECOVERY IN JAPAN

INTRODUCTION
The March 2011 earthquake disaster in Eastern Japan produced devastation on an almost unimaginable scale. In the immediate aftermath, the country focused on meeting basic needs: ensuring safety, bringing in food and finding shelter for those in need. Then came the realities of the economic impact. As a major global supplier of electronic parts, Japan is a crucial link in the production lines of the automotive, semiconductor, and consumer electronics industries. Production lines had to be brought back quickly to stabilize the supply chain.

Renesas Electronics, the world’s top microcontroller producer and a key supplier to the automotive sector, worked together with Applied Materials and many others to quickly overcome tremendous difficulties to return their flagship Naka fab to production in under three months. We thank Renesas for sharing their remarkable story of revitalization with our Nanochip readers. It is but one of many stories from Applied Materials customers in Japan reflecting the courage and power of people working together.

CONTAINING CHAOS AT NAKA FACILITY

The catastrophic earthquake on March 11, 2011 caused significant damage to the eight factories Renesas Electronics operates in the Kanto and Tohoku regions. The company was forced to suspend operations at these factories, effectively halving its production (preprocessing) capacity. The Naka Factory—located in Hitachinaka City, Ibaraki Prefecture (see map)—was seriously damaged and for a period of time following the earthquake, workers there could not even make contact with the Renesas headquarters in Tokyo.

The day following the quake, managerial staff, volunteer fire fighters and employees responsible for utilities gathered at the Naka Factory to conduct an inspection of facility damage. However, due to the scarcity of electricity and water, simply confirming the current status presented significant difficulties. The earthquake shattered the inside of the Naka Factory. Walls inside cleanrooms fell, and steel beams were exposed. Metal brackets used to firmly secure manufacturing systems were twisted and deformed. Semi-conductor lithography systems were so damaged that they had to be shipped to the manufacturer for repair, and more than 1,400 reticles lay scattered in the debris. Hideki Shoji, a Senior Engineering Manager in Facility Engineering at the Naka facility said, “...the damage was beyond imagination. We did not know where to begin.”

Ten days after the earthquake, on March 21, Renesas launched a recovery plan aimed at resuming production on September 1. This involved prioritizing the recovery of power and water supply facilities, exhaust facilities, cleanrooms and other production infrastructure. Eventually, a total of 9,500 people would work to restore the infrastructure at the Naka factory, and an estimated 80,000 people would participate in some way in the company’s overall recovery activities.

THE JOURNEY TO RECOVERY

As a key supplier to Japan’s semiconductor industry, Applied Materials’ response to the Japan earthquake disaster was swift and deliberate. Within days of the quake, Applied mobilized a response team with members from within Japan, the U.S. and across Asia to assist customers in getting their fabs back into production. This included field engineers, logistics and operations staff, parts suppliers and project managers who would work side-by-side with customers throughout Japan, often around the clock, for months to come.

Renesas’ Naka fab was one of the hardest hit. On March 28—the first day Renesas approved the fabs for re-entry—Applied’s early response team began a site tool audit. Of the hundreds of Applied tools installed in the Naka facility, more than 90% sustained some form of damage. In the first week of April, this response team of 15 Applied systems engineers devised a recovery plan based on tool priority. Phase 1 recovery efforts, which addressed the most critical tools, began immediately, and were completed by April 23rd. This was just 14 days after full power was restored to the Naka facility, and only one day after key support systems, such as process gases, were enabled.

In the midst of continuing magnitude five aftershocks, rolling blackouts and transportation shutdowns, Renesas organized the efforts of engineers from Applied and other suppliers into shifts that worked 24 hours a day. In all, at the peak of recovery activities in early April, Renesas estimates that more than 2,500 engineers worked on the project. By the end of April, Applied Materials alone had assembled a site team of 155 service engineers and field personnel; 90% of these were brought in from outside the normal Naka site team (normal staffing pre-earthquake was 15), with 35% from overseas.

In addition to the tool recovery teams, Applied Materials also assigned site managers to coordinate the local and global workforce and assist with on-site project management during Phase 2. To support Applied teams on the ground in Japan, Applied headquarters assigned additional administrative and support personnel to ensure a smooth management of logistics for service engineers.
reassigned to the Naka recovery. This team handled travel, local accommodations, communications and safety protocols and training.

One critical aspect of the recovery involved supplying primary and spare parts for damaged equipment. Applied’s recovery task force worked closely with internal spare parts depots and parts suppliers around the world to ensure that the needed parts and components were shipped immediately to Japan. This was a major effort, not only to get the parts safely and quickly to Japan, but to get them moved to the Naka fab site through a devastated countryside, where transportation was still difficult.

Phase 2 tool recovery on Applied equipment at Naka was completed by May 7th, less than two months after the earthquake.

George Yi, Vice President of Field Support Operations for Applied Global Services, noted that although disaster is unpredictable, Applied’s response wasn’t. “We had no doubt that our global workforce would be ready and willing to support the recovery. In fact, we had over three times as many volunteers as needed for the various recovery projects. We had no uncertainties that our employees would have the tools and training necessary to work safely in a difficult environment.” Yi said.

On April 23, just six weeks after a disaster of epic proportions, Renesas was able to start test runs for 200mm manufacturing lines. Kazunori Horita, a Supervisor in the Manufacturing Department at the Naka factory noted, “…we launched test runs for the first lot after the disaster, which were named ‘Kizuna’ (literally translated as “bonds among people”).” Two days later, on April 25th, test runs were also performed on the Naka 300mm manufacturing lines. By June 1, the company was able to begin mass production—three full months ahead of the planned September target.

In a letter of appreciation to Mike Splinter, Applied Materials President, CEO and Chairman, Yasushi Akaso, President of Renesas Electronics Corporation, wrote, “I sincerely appreciate your kindness to dispatch your staff to our Naka Factory, which was absolutely indispensable and beneficial for us to accelerate the recovery. Under conditions like aftershocks, strong winds and heavy rains, your staff spent big efforts to restore our production systems which are the lifeblood of Naka factory.”

This amazing result will be remembered by all who contributed as a true testament to the human spirit, to resilience and to the power of collaboration. In a word, it is really about “Kizuna.”