DRIVING SEMICONDUCTOR MANUFACTURING BUSINESS PERFORMANCE THROUGH ANALYTICS
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Semiconductor manufacturing is amongst the most demanding businesses. Complex production processes and systems present challenges to scaling, plant utilization, quality and yield. The sophisticated equipment, ultra sanitized manufacturing facilities and a high degree of automation demand enormous investments running into billions of dollars. Technological changes, shrinking product lifecycles, competitive pricing, and the demand for larger new generation wafers with tighter production uniformity, are bringing unprecedented pressure on the industry. The good news is that manufacturers have realized this and are rising to the challenge. They are using multiple methods including data analytics.

Investments in data management and analytics are growing thereby helping companies to predict process behavior, to identify and isolate defective tools and recipes, correlate parameters to help improve yield and provide better visibility to management across the plant. The allure of analytics is in the precision with which it can sift through complex data and improve efficiency, yield, decision making and time-to-market.

This paper examines some of the analytical techniques, predictive models and control charts that can be leveraged by the semiconductor industry. These methods can aid in the improvement of process diagnostics, optimization and remodeling. The improvements allow manufacturers to respond strongly to emerging needs.

Semiconductor Industry Overview

The industry has been a key driver for economic development. It has powered the growth in computers, consumer electronics and the Internet industry. Semiconductors are becoming indispensable in healthcare, automobiles, defense and wireless communication. Globally, they play a pivotal role in enabling other industries: US$ 1200 billion in electronic systems business and US$ 5000 billion in services alone, accounting for 10% of world GDP.

There are two critical parameters for semiconductor manufacturing:

**Wafer size** - This is the diameter of the silicon wafer, currently transitioning from 300mm to 450mm, representing a major technological inflection. The bigger the wafer, the larger the chips from it.

**Node** - This is the typical half-pitch for a memory cell which is often used to indicate how small the transistors on a chip are and also indicates how advanced a chip fabrication line is. The smaller the node, the greater are the number of chips.

The technology transition from 300mm wafer size to 450mm has major capex implications. The transition demands higher operational efficiencies, minimizing downtime of equipment and improving yield from the newer generation of fabs. Leading semiconductor companies are relying on analytics to deliver better information and enable the improvements.
The following illustration represents the semiconductor manufacturing process and its key challenges:

![Semiconductor Manufacturing Overview](image1)

**Manufacturing Costs**

An interesting aspect of semiconductor manufacturing is that the front-end contributes 90% of capital costs and 80% of lead times. This also provides a clue to where problems need to be solved. Analysis highlight the fact that investments in Equipments and Processes have the highest share of manufacturing costs and any improvement in equipment utilization will have a corresponding and significant impact on top lines.

![Manufacturing Cost Contribution in IC’s](image2)
Data Sources and Complexities in Semiconductor Manufacturing

Manufacturers have traditionally invested in methods to analyse specific processes or equipments to create solutions that enhance productivity, yield and quality. But they may fail to carry out a holistic analysis. This is due to lack of visibility (or access to data) across functions. For example, a manufacturing problem is easy to isolate. But integrating design and manufacturing, or tightly mapping process recipe with design, requires new approaches to data management and analytics. The holistic approach delivers better results than traditional management methods. Better performance, higher efficiencies and faster ramp up of yield can be expected.

Fortunately, data is plentiful. Multiple systems and processes generate terabytes of it, requiring integration and a holistic approach to analysis. These include:

**MES Data (Manufacturing Execution Systems)** – Manages shop floor operations

**Equipment Data** – Like temperature and pressure from equipment

**ERP and Planning Data** – Transactional data

**Recipe Data** – Routing data within the shop floor

**Metrology Data and Defect Data** - Measurement of process and equipment generated defects

**Parametric and Electrical Data** - Measurement of electrical specifications and characteristics of chips

Additionally, there are four levels of granularity one has to look into while analyzing semiconductor process data:

**IC Level:** This is the lowest level of granularity wherein data is specific to an individual chip.

**Site-Level:** The next level of granularity is the test site.

**Wafer-Level:** At the next level, there is a wafer.

**Lot-Level:** At the top level, there is a batch of wafers called Lots. A typical full Lot has 25 wafers.

Losses in Manufacturing

There are several losses in wafer manufacturing that demand attention. These include equipment downtime, yield losses, setup time, batching/ dispatching, rework, speed loss, lot wait and hot lots. The losses indicate that the scope for data mining and analysis is vast. Analysis can result in advance indicators of processes that are degenerating along with Root Cause Analysis across design and manufacturing processes.

Semiconductor Metrics

Semiconductor manufacturing shares challenges similar to other industries like consumer electronics that include complex and outsourced supply chain, shrinking product life cycles, energy efficiency etc. But it does have a set of unique challenges. These include yield, utilization and Overall Equipment Effectiveness (OEE).

**Equipment Utilization**

Equipment utilization measures the duration for which an asset was engaged in a processing activity. Precise definitions and measurements of utilization vary from company to company. For practical reasons, time credited to utilization may include actual processing time, short periods during which the equipment is idle while operators perform handling, recipe download and metrology tasks required between consecutive process steps. Since the equipment is highly capital intensive, any increase in utilization would increase productivity and could substantially increase returns.

As an example, photolithography comprises the highest concentration of capital expense of all equipments in a fab. Maximising the utilisation of photolithography tools plays a major role in improving the output of the fab.

**Yield** - In semiconductor manufacturing the overall front-end manufacturing yield is the product of the wafer-level yield of the fabrication process (line yield) and the die-level yield of the electrical die sorting process (die yield).
Line yield expresses the fraction of the wafers that emerge from fabrication as completed wafers available for electrical die sorting. Wafers may be accidentally broken or scratched during fabrication for a variety of reasons starting with handling mechanism failure to equipment malfunction and operator errors. The line yield metric reflects equipment reliability, process control, and operator proficiency.

Die yield is the fraction of the total die on a wafer that passes Electrical Dies Sorting (EDS). Typically, die yield accounts for a larger loss of potential output than does line yield. This is because integrated circuits ("die") printed on a completed wafer rarely function properly. In the EDS process each die on the wafer is tested to see if it functions. Inoperative dies are discarded.

**Overall Equipment Effectiveness (OEE)** - OEE is an all-inclusive measurement of semiconductor equipment and manufacturing productivity. OEE approaches the problem of equipment complexity to implement permanent productivity improvement. OEE is the product of six equipment losses grouped into three categories—availability, performance efficiency, and rate of quality—as follow:

<table>
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<th>Availability</th>
<th>Performance Efficiency</th>
<th>Rate of Quality</th>
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<tr>
<td>1. Unscheduled equipment down time</td>
<td>3. Idling and minor stoppages</td>
<td>5. Rework</td>
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<td>2. Scheduled equipment down time</td>
<td>4. Reduced speed of equipment</td>
<td>6. Wafer or yield losses</td>
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The three groups of losses are then multiplied to determine the OEE % value:

\[ \text{OEE} = \text{Availability} \times \text{Performance Efficiency} \times \text{Rate of Quality} \times \frac{1}{100} \]

A solution to be effective in a semiconductor context has to address these three metrics to have a meaningful impact.

**Analytics for Insight and Decision Making**

Using analytics can help fabs identify systemic factors like defective tools/recipes that degrade productivity and efficiency, correlate parameters in real time to ensure yield improvements and failure analysis. Analytics today is addressing complex questions that have foxed managers for long:

- Why do certain lots go through rework process? Is there a pattern?
- Why did the yield drop dramatically last week for a certain product while yields for similar products remained flat?
- Why do we encounter intermittent yield and quality excursions for certain products?
- What is the worst equipment path that we need to avoid?
- Why is there a huge variation within certain production batches while other lots show a tight distribution?
- Can we define an optimal equipment path to maximize yields, quality and reliability?
- Why is certain equipment performing better (or worse) than other similar equipment?

**Analytical Methods and their Application**

Metrics & KPIs - Newer system and process metrics that are integrated with KPI definitions are enabled by analytics (examples: Rework as a percentage of Revenue and Scrap as a percentage of Revenue). These metrics are delivered over intelligent dashboards with real-time indicators of shop floor conditions, equipment and process health, allowing executive to arrive at faster and more precise decisions.

- Can you tell me why we have had 20% scrap for this product?
Statistical Process Control (SPC) Mechanisms - Process or product metrics are analysed for continuous action to improve process capabilities. Many tools, including a Monitor Chart, can be used for the purpose.

Figure 4: Monitor Charts for SPC
Fault - Detection, Classification and Prediction - This is a technique for monitoring and analyzing variations in tool and/or process data. It helps surface anomalies. Fault Classification builds on that with techniques to determine the cause of a fault. Both methods are used together as Fault Detection and Classification (FDC). Fault Prediction is the technique of monitoring and analysing variations in process data to predict anomalies and faults before they occur.

Monitoring through Control Charts - Control Charts are efficient methods of controlling and optimising processes within specified limits. The specifications need to be set such that variations within the specifications have negligible impact on device characteristics. Other control charts such as Exponential Weighted Moving Average (EWMA) detects small drifts by retaining the measurement of several previous lots, with the most recent lot having the greatest weight. Consistent yield differences between etching equipments or any other critical equipment in a fab can be diagnosed through this and preventive maintenance can be initiated rather than shutting down the equipment for root cause analysis.

Root Cause Analysis - This is a structured approach aimed at identifying causes using historical data. In semiconductor manufacturing this can be used to identify:

- Yield with respect to Product/ Product Groups/ Sites
- Yield at Operation/ Processes
- Yield at Equipment/ Operation combination
- Scraps at Equipment/ Operation/ Product Combination
- Correlation analysis between different parameters within the operation or past operations
Failure analysis - Failure analysis is the process of determining how or why a semiconductor device has failed. Process owners can determine the root cause of the failure and not just the intermediate causes that occur after the root cause triggers the failure. Failure analysis is necessary to prevent similar failures in the future.

Predictive Maintenance - Historically, the semiconductor industry performed maintenance after equipment failure. This has given way to preventive maintenance, where periodic maintenance, it is hoped, will reduce failure. More recently, Condition Based Maintenance (CBM), enabled by the advent of monitors and sensors onboard the equipment, have begun to provide views of the equipment's operating conditions in real time. Advanced analysis techniques such as real-time Fault Detection and Classification (FDC) are used to identify whether performance indicators have deteriorated to a predetermined threshold or control limit. The CBM applications trigger a maintenance event in factory systems when required.

The next logical step is to develop a predictive model of maintenance events. This is done through data and applying equipment degradation model to predict the equipment’s Reasonable Useful Lifetime (RUL). This would need sophisticated analytical tools and solutions that can alert ahead of equipment breakdown to avoid unscheduled downtimes. This would allow the fab to optimally schedule for the preventive maintenance, taking into account work schedules, yield, parts inventory, and other parameters.

Predictive Models - To maintain a competitive edge, newer models for wafer yields, cycle times and optimum equipment paths are required. Analytical forecasting tools and methods are needed to:

- Understand the correlation between parameters, equipment and process operation
- Optimize equipment paths for a product/ process
- Create models for yield based on previous process parameters
- Create Models for Scrap estimation

Figure 6: Root Cause Analysis and Correlation matrices
Typical predictive models used would be neural Networks, Decision Tree or Regression Analysis to arrive at conclusions.

These are illustrative examples of the role analytics can play in semiconductor manufacturing companies to ensure they remain competitive.

The Future for Analytics and Semiconductors

Analytical solutions with data mining and advanced modeling features will be central to the ability of the semiconductor industry to meet customer requirements. Performance improvements will enable the industry to neutralise margin erosion, ensure faster-to-market capabilities as product lifecycles shrink and adapt to new market conditions. The survival for many in the industry could be directly related to the ability to deploy analytics.

Innovations that include interactive reporting, enhanced GUIs, collaboration features, the ability to integrate multiple data sources will help foundries and IDM’s within the semiconductor ecosystem achieve higher efficiency and reliability with optimised fab utilization. The future of analytics in the industry cannot be discounted or overlooked. It is a key ingredient of future fabs.

Note: All screenshots in this paper have been modeled using SAS Software.
About the Author

Manoj Ramanujam is part of Presales and Solutions group in Wipro's Semiconductor and Capital Equipment business. In his role, he is responsible for creating semiconductor-industry-specific solutions and offerings within the Enterprise Applications space. He has rich experience in architecting enterprise solutions in Supply Chain domain involving large scale ERP implementations across Semiconductor, Energy and Process Industries.

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