Enhanced vacuum security using advanced sub-fab monitoring and data analytics

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Sub-Fab Fault Detection and Classification (FDC) software platforms collect, integrate and analyze operational data.

The ability to provide the reliable high-quality vacuum environment that most semiconductor manufacturing requires is an often and easily overlooked aspect of the whole fab process. The unexpected failure of a vacuum pump can bring significant disruption to the manufacturing process, potentially imposing a heavy penalty in lost productivity and scrapped product. The sub-fab, where vacuum and abatement systems are typically located and so named because it is located literally below the fab floor, has evolved dramatically over the years, from simply a location outside the fab in which to house supporting equipment, to an environment that is in many ways as sophisticated as the fab itself. Just as manufacturers have adopted advanced monitoring and data analytics to optimize fab operations, they are finding significant benefit in applying the same techniques to sub-fab operations. Sub-Fab Fault Detection and Classification (FDC) software platforms such as Edcentra, Edwards' newest equipment monitoring, data acquisition and analytics platform collect, integrate and analyze operational data from the sub-fab, providing a comprehensive solution to vacuum security.

The challenge of cost-effective innovation

The semiconductor industry faces many challenges, including the high pace of innovation and the need to constantly improve operational efficiencies, decrease costs, reduce adverse environmental impact and ensure the safety of personnel in the fab and residents of the surrounding community. Some of the ways these challenges have been met in the past no longer apply. For instance, although there is still device scaling in new technology nodes, the type of simple geometric device scaling driven by Constant-Field Scaling rules [1] – to drive innovation, improve efficiency and reduce costs per die - effectively ran out a decade ago.

Innovation has continued, though along very different lines, introducing ever more complex device architectures and increasing the use of exotic materials and manufacturing methods, such as epitaxial and atomic layer deposition. These innovations have all extended development time and time-to-market, driven up cost, reduced efficiency (lower yields, more frequent equipment preventive maintenance cycles) and brought new and higher environmental restrictions (stringent local, national and international regulations, as on CO_2 emissions) and safety challenges (toxic precursor materials and waste products). Delivering timely and cost-effective innovation is now a major issue for the semiconductor industry. In response to this challenge, manufacturers have recognized the strategic necessity of integrating and analyzing all the information available from their processes. These manufacturers are therefore starting to adopt an integrated fab data and information management approach that accounts for all the factors affecting time-to-market at the lowest possible costs. The sub-fab and associated support systems cannot be omitted from this approach.

The importance of vacuum

Most of the critical steps in a chip manufacturing process are conducted under high vacuum conditions and vacuum quality is one of the most important parameters in these process step. Vacuum quality is a combination of vacuum level and vacuum content. No vacuum is absolute, and there are always trace amounts of non-process gases present in process chambers that can have a major impact on the process, if not controlled.

As any fab equipment or process engineer will tell you, maintaining vacuum quality is so important that pumps are almost never shut off and process chambers are almost never brought to atmospheric pressure, even when idle for long periods of time. Maintenance activities on process chambers are performed, whenever possible, with minimal or no exposure to atmosphere. This is for a very good reason: once a chamber has been vented to atmosphere it may take a very long time to return it to the previous known-good-vacuum state, affecting equipment uptime and process yield.

The vacuum state can therefore affect wafer quality and overall fab costs through its effect on yield or through losses incurred as a result of unplanned vacuum failures during wafer processing. For example, insufficient vacuum levels or trace amounts (ppm level) of unintended gases, such as O_2 or H_2O, in an ion implant process can greatly reduce the stability of high voltage power supplies, leading, in turn, to fluctuations in ion beam current, non-uniform implant conditions on the wafer, and ultimately to poor and non-reproducible wafer yields. A pump "crash" during a batch process that causes the scrap of an entire production batch–normally 125 wafers–is very costly in both direct product loss and process downtime. Even in single wafer process, unplanned pump failure can cause significant losses as some process tools require days or weeks to requalify.


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Fab managers face a difficult choice between the costs of vacuum failure and the costs of too frequent maintenance. Optimizing this choice is one area where sub-fab equipment monitoring and advanced analytics can make an important contribution. Most effective optimization occurs in an adaptive maintenance regime, where pump maintenance is performed in parallel to tool maintenance, thereby virtually eliminating vacuum pumps as a cause of lost tool time. Long prediction horizons are required for successful adaptive maintenance, enabling the longer PM intervals (months) typical of sub-fab equipment to be synchronised to the shorter PM intervals (weeks) of the fab process equipment. For this to happen, and thereby assuring sustained vacuum quality, additional types of sensors and improved predictive capabilities and time horizons will be needed. The remainder of this paper highlights Edwards' exploratory work on using mechanical vibration sensor data to obtain a reliable and long prediction horizon for mechanical failure modes [2].

Failure Prediction Using Vibrational Sensor Data

Monitoring vibrations to assess the health of rotating machines has a long and successful history. Intrinsic bearings frequencies can be calculated from rotation speeds, and wear-generated perturbations to these frequencies can be detected to predict bearing failures and other mechanical failure modes. However, these existing methods do not translate well to a semiconductor environment where process-induced failure modes are more frequent. The sub-fab working environment also tends to be extremely noisy from a vibration spectrum perspective and the effects of process induced failure modes on standard vibration spectra are largely unknown.

We have developed a new method of unlocking key predictive information (Fault Detection or FD) from vibration data, based on a "fingerprinting" technique, which translates complex, noisy data into a single dynamic coefficient that can be compared easily with existing predictive maintenance parameters. Further vibrational sub-band analysis provides specific failure mode identification and root-cause analysis, thus providing a key fault classification (FC) capability. This method will be referred to as Vibration Indicator or VI from here on.

Results

FIGURE 1 shows an example of the power of VI to extend visibility of a catastrophic bearing failure in a fab working environment. A departure of VI from zero indicates the emerging signature of mechanical bearings wear. The time horizon in this example is at least 60 days, providing extended visibility and increased process security.

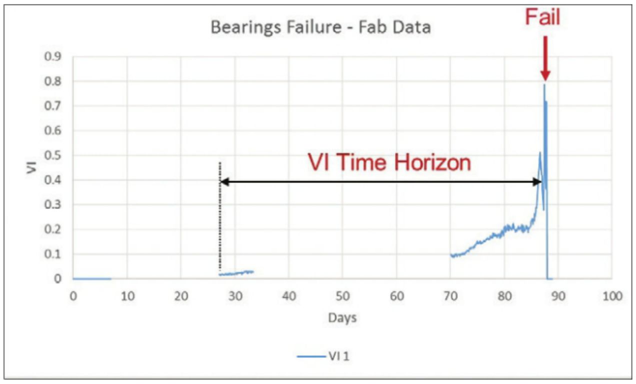

FIGURE 1. 90 day sample data of a bearings failure in a fab environment. Data was not collected continuously.

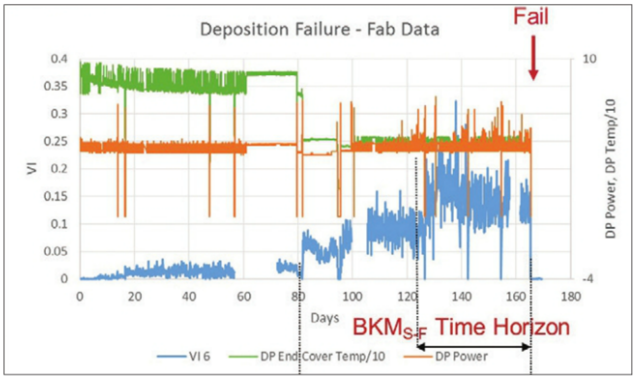

FIGURE 2. Evolution of VI versus traditional pump parameters for a deposition failure mode on a production LP-CVD Si_3N_4 deposition process. Key: VI (blue), DP Power (orange), DP end-cover T (green).

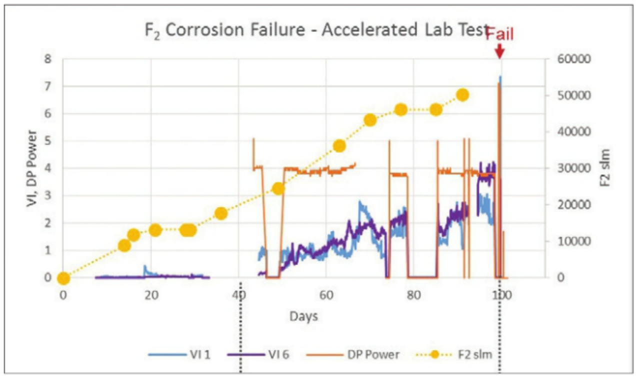

FIGURE 3. Accelerated lab testing of F_2 corrosion induced mechanical failure mode. Key: Accumulated F_2 flow (yellow); DP Power (orange): VI (blue and purple).

A second fab-based production environment example, taken from an LP-CVD Si_3N_4 batch deposition process and shown in **FIGURE 2**, illustrates the sensitivity and predictive power of VI compared to traditional pump parameters: power and temperature. The ultimate cause of failure in this case was deposition-related. As can be seen, from day 60 onward changing process conditions caused a step-change in the temperature. The power curve develops patterns of spike behavior around day 120. Previously existing best-known-methods (BKM) for predictive maintenance, based on analysis of power and temperature data, can detect this emerging behavior using spike-area and frequency-based techniques, in this case with a time horizon of 40 days. The key observation in this example is that VI (blue curve) reacted immediately to an increased deposition of condensable materials, which led directly to an equipment failure 90 days later. The VI provided a time-to-failure horizon of 90 days (55% of observed pump life), more than double that of traditional parameters.

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Accelerated lab testing provides further evidence of the extended time horizon VI affords. **FIGURE 3** shows the results of a lab-based accelerated fluorine (F_2) corrosion induced mechanical failure mode, with large F_2 gas flows injected into the vacuum system and pump. The traditional power parameter is completely insensitive to the F_2 flow and resulting corrosion. The VI, by contrast, shows a linear corre-

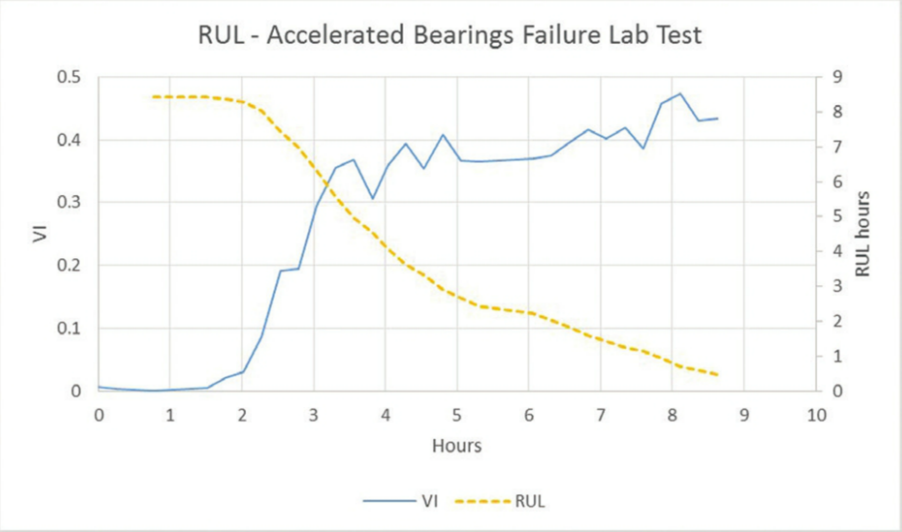

FIGURE 4. RUL estimates from an accelerated bearings failure lab test using VI metric.

lation with total accumulated flow, providing both early detection and a measure of the severity of the developing problem.

A second lab-based test (not shown) investigated the effects of oil contaminants and again confirmed the ability of VI to detect and quantify failure modes inaccessible to established methods. As in the corrosion example, a linear correlation was found between accumulated contamination and VI, while power measurements proved to be completely insensitive to oil contamination levels.

These show that VI can significantly extend the time horizon of equipment failure modes, well beyond current predictive capabilities and into the regime where effective maintenance pooling and the resultant cost savings can be realized. Moreover, these results can be translated into precise RUL predictions using various parameter estimator techniques, complementing standard Weibull techniques. **Figure 4** shows the results of an accelerated bearings failure lab test for a dry pump, comparing VI and estimated RUL.

Performance comparison

Tables 1 and 2 compare and contrast VI performance with mainstream SPC-like control methods, such a single parameter threshold monitoring and multi-variate analysis (BKMS-F), in terms of detection capability, sensitivity, prediction time horizon and hit rate vs. false positives. **Table 1** shows that VI considerably extends prediction time horizon and, based on data gathered to date for detectable results, has demonstrated a 100 percent hit rate with no false positives. From **table 2** we see that VI extends predictability to mechanical failures, has high sensitivity, and detects problems as soon as they begin.

Summary and conclusions

The need for increased operational efficiency in semiconductor manufacturing is driving the development of smarter interconnected vacuum sub-systems and the adoption of integrated data and information management technologies. A case

	FAULT CONDITIONS				
	Mechanical	Process Induced			
	e.g. Bearings	Process Deposition	Pump Corrosion	Exhaust Blockage	Ingestion
	Prediction Time Horizon				
SPC	-	Fixed threshold, no advisory			-
BKM$_{S-F}$	-	2-4 weeks	2-3 weeks	1 week	-
VI	**Months**			**-**	**Months**
	Hit Rate / False Positives				
SPC	-	70% / 20%			-
BKM$_{S-F}$	-	85% / 5%			-
VI	**100% / 0%**			**-**	**100% / ?**

TABLE 1. Time horizon, hit rate and false positives.

	FAULT CONDITIONS				
	Mechanical	Process Induced			
	e.g. Bearings	Process Deposition	Pump Corrosion	Exhaust Blockage	Ingestion
	Detection Capability				
SPC	N	Y	Y	Y	N
BKM$_{S-F}$	N	Y	Y	Y	Y
VI	**Y**	**Y**	**Y**	**N**	**Y**
	Sensitivity				
SPC	-	Can only detect critical conditions Very subject to noise			High risk of false alarms
BKM$_{S-F}$	-	Can detect problems only when they have reached a near critical level			Can detect event but not infer severity
VI	**As soon as physical change occurs**			**-**	**Can detect permanent damage**

TABLE 2. Fault conditions, improved detectability and sensitivity.

study described the combined use of the EdCentra sub-fab information management system and an innovative approach to vibrational analysis. Compared to current main-stream methods, VI provided an extended, and in some cases unique, predictive maintenance capability for mechanical pump failures and a very high level of sensitivity. For the data gathered so far on detectable faults, the hit rate has been 100 percent, with no false positives. Finally, advanced analytics and VI considerably extended the prediction time horizon from weeks to months. Together with existing predictive algorithms and methodologies for pumps, abatement and ancillary equipment, the capabilities provided by advanced information management and innovative monitoring technologies like VI have the potential to significantly reduce costs and increase productivity.

Acknowledgements

The author would like to acknowledge and thank Antonio Serapligia and Angelo Maiorana for their groundbreaking work on vibrational analysis, and David Hacker and Alan Ifould for their inputs on the challenges and opportunities of sub-fab equipment maintenance and many fruitful discussions.

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