APC in the Semiconductor Industry, History and Near Term Prognosis

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Abstract - This paper presents an abridged history of Advanced Process Control (APC), including both Fault Detection and Classification (FDC) and Model Based Process Control (MBPC), both within TI and in the semiconductor industry. While TI was an early leader in univariate fault detection in processing tools, other manufacturers have by now implemented such methodologies. For MBPC, the MMST program gave TI a lead, but others are now following that path. For TI and the semiconductor industry as a whole, the current thrust is to develop and implement multivariate APC methods into the manufacturing operations. This paper describes the complexity of the execution of these tasks, and lists some of the available tools that are requisite for implementing these plans.

APC Background

The precursor to APC (Advanced Process Control) in semiconductor manufacturing operations, has historically been the SPC (Statistical Process Control) activities that have become prevalent in the 60's. A fundamental operating principle behind SPC is that the process parameters - the hardware settings - be held invariant over long periods of time. SPC then tracks certain unique, individual metrics of this process - typically some wafer state parameter - and declares the process to be out-of-control when the established control limits are exceeded with a specified statistical significance. While this approach has some established benefits, it suffers from a) its myopic view of the processing domain - looking at one, or only a few - parameters and b) its delayed recognition of a problem situation - looking at metrics that may only be generated once in a while or with a significant time delay relative to the rate of processing of wafers.

In retrospect, it is clear that all of these constraints have to be removed when pursuing the ever-increasing demands placed on manufacturing operations due to the well-known problems associated with the continuing decrease in feature size. Specific requirements are that:

1. processing anomalies be determined by examining a much wider domain of parameters
2. processing anomalies be detected in shorter timeframes; within-wafer or at least wafer-to-wafer
3. wafer state parameters be measured, or estimated, frequently
4. processing emphasis be focused on decreasing the variance of the wafer state parameters instead of controlling the variance of the setpoints

APC is the current paradigm that attempts to solve these four specific problems. Under this general heading, the FDC component addresses the first two requirements, MBPC addresses the last two.

History of APC at TI

Elements of Advanced Process Control, including both Fault Detection and Classification and Model Based Process Control have been utilized within various TI Wafer Fabs for about a decade. FDC evolved from the early EMS (Endpoint Monitoring System) that was an embedded fault detection system built into the PAC 150PC series of single wafer plasma etchers [1]. This system analyzed the endpoint trace of every wafer in relation to the endpoint trace of a good "reference" wafer, after the completion of the etch process.

When an anomalous endpoint signal shape was detected, the system alerted the operator or shut down the etcher, based on a user-defined action relative to the severity of the anomaly. This methodology had a clearly apparent benefit as it automatically identified anomalous process conditions for specific wafers as soon as the wafer finished processing; these wafers could be examined individually and disposed of as appropriate. When the anomaly was significant, it automatically terminated processing, hence saving the remaining wafers from being misprocessed.

MBPC was first developed in SFAB for epi deposition [2]. The model was simply:

deposition thickness = rate * time

and this model was adjusted based on intermittent measurements of the actual thickness. Using the adjusted model, the deposition time was recalculated to keep the deposition thickness at the target value. This method improved Cpk, as expected, over running in an open-loop configuration using a set deposition time. In addition, it provided other significant benefits by reducing the number of qualification runs, as well as the time and the number of pilots required to requalify a process after an R&M operation.

From a historical perspective, these methods were readily accepted and integrated into production because:

1. both techniques were conceptually simple, hence easy to implement and disseminate
2. there was a clearly defined benefit for both techniques
3. the original implementation of these techniques was a reasonably "low-cost" effort from both a hardware and software points of view

Current Status of APC

Status at Texas Instruments

The FDC activity started by the EMS system has diffused throughout all the Wafer Fabs across TI. The driving force was the realization that the methodology was readily applicable to any other processing tool that generated some signature (e.g. furnace temperature profile, current profile of the power supply during resist spin operation, etc.). So the methodology was provided in a stand-alone application, available to connect to various tools. This embodiment, ECR (Electronic Chart Recorder), has been fanned out and is currently operational in most of TI Wafer Fabs. A slightly different embodiment (Cruiser) was generated locally in one Fab where it is connected to a very wide base of processing equipment. In both cases, the analysis is univariate, where faults are detected based on data from a single sensor.

MBPC has taken two distinct paths within TI. SFAB has continued with the upgrade of their deposition control activities, with "home-grown" software, and have shown significant operational benefits using univariate MBPC. Meanwhile, during the MMST program [3], TI developed the basis of what later has become known as ProcessWORKS [4], a system that contains all the elements necessary for automated multivariate MBPC. This embodiment is currently being developed in SPDC and SFAB, in anticipation of TI-wide deployment.

Status at Other Semiconductor Manufacturers

Most semiconductor manufacturers are currently using sensor signals in a univariate fashion for applications such as endpointing for oxide CMP, tool-state information from RF sensors, etc. Table 1 summarizes these activities, and basically shows that everyone participates in univariate FDC and some manufacturers are heading to multivariate FDC. One major remaining question is whether to do these analyses at the tool or factory level.

APC Directions

It is clear from interactions at SEMATECH and other national level meetings that APC is being accepted and pursued by all major semiconductor manufacturers. One interesting point is the differ-

Company	APC Activities
AMD	Wafer Sleuth; AMD/Honeywell/NIST APC activity
HP	originated Wafer Sleuth
IBM	univariate FDC with Process Guard
Intel	univariate FDC for several years
Motorola	multivariate FDC with ModelWare
TI	univariate FDC, univariate and multivariate MBPC, Wafer Sleuth, PCA/RTSPC for multivariate FDC

Table 1. Summary of APC activities at the major semiconductor manufacturers

ent emphasis being put on the various aspects of this problem by the different players. For some, the emphasis is on Fault Detection, to prevent further wafer misprocessing. For others, the prediction of wafer state properties is more significant. Such a diversity in the visions and expectations for FDC is also complicated by the variety of the nomenclature used by different organizations. However, all these tasks are part of the APC "big picture", which is shown in Figure 1. This figure summarizes the APC paradigm, as perceived in the SEMATECH J-88-E project [5,6]. The three major blocks represent the hardware, process and wafer state parameters. Assuming that direct wafer-state sensors are not being used (as those are typically unavailable in OEM equipment, at this time), all APC activities can be represented by the models **f**, **g** and **h**. The use and requirements of these models will be elucidated in the following sections.

Fault Detection

TI, and many other semiconductor companies, have been active in univariate FDC for a number of years. With the evolution of process sensors that provide a variety of signals from the process in real time, the trend is clearly towards multivariate FDC. With the multiplicity of sensor signals, the chance of detecting faults is significantly increased. However, this multivariate FDC places the problem in a significantly different realm, due to new issues that now have to be addressed, such as:

- sensor data acquisition, data transfer and communications to a computational algorithm have to be seamlessly automated
- data pre-treatment algorithms are required
- complex computations (PCA, PLS, time-series analysis...) have to be performed to accommodate for the correlated, redundant data sets from different sensors
- these algorithms have to be made robust against the natural drift in the sensors and the intermittent step-changes in the system at times when the machine is cleaned
- these computations have to be automated, so that they require no manual intervention
- whether FDC is performed during or after the processing of individual wafers; this decision defines a multitude of data acquisition and analysis options and requirements

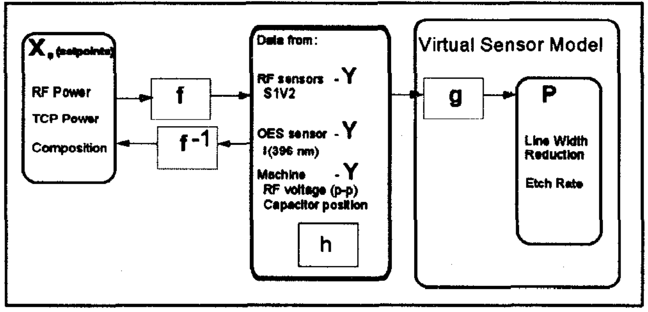

Figure 1. Model representation of APC components

It is worth emphasizing that the first task of FDC is *fault detection*, i.e. the determination that during the processing of a particular wafer, the sensor signatures indicate a "non-normal" state. This requires that a model **h** be generated that determines process state anomalies from the multitude of machine state and process state sensor data. This is a bigger problem than might first be envisioned, since the "normal" state is not a stationary point, but a slowly changing trajectory through time. The clearest example of this is the noticeable degradation of the endpoint signal obtained from the machine state data in any plasma etcher. This signal decreases continuously, as the window transmittance degrades due to the gradual accumulation of a residue on this window. So measured by this parameter, the normal processing state metric decreases continuously, while there is of course no "fault", or even a drift, in the system. The FDC methods have to distinguish between this type of sensor drift, and the other source of drift; that due to the changing "state" of the processing chamber. This is typically attributed to things such as: wear of the electrodes, buildup of residue on the walls of the process chamber, etc.

Given these constantly changing sensor signals and chamber state during the normal operating cycles between successive cleans of the equipment, it is clear that models **can not** be generated based on the concept that specific settings on the equipment generate a specific set of values for all the sensor signals. Models have to comprehend the concept of moving means and the correlation between multiple sensor signals (a covariance matrix).

So an absolute requirement of these FDC methods is that they be robust against the normal drifts in the system for extended time periods. The primary reason for this, of course, is that the use of any such methodology in a manufacturing operation requires that there be minimal model "upkeep" as well as a minimal number of false alarms. The "extended time period" is somewhat undefined, and will be different for different tools. As a guideline, models have to be valid for at least ~ 5000 wafers processed over a period of ~ one month, including changes incurred at the periodic chamber-clean operations.

Once a fault is detected, the next task is *fault classification*. This task is performed with models **f^{-1}** and **g** (which have to be generated for a given system). These specify the possible causes of a fault (e.g. pressure was too high) and determine the effect of the fault on the wafer state (e.g. etched linewidth is too narrow), respectively. Model **g** is typically called a "Virtual Sensor", as it provides wafer state data from the available sensor signals in the absence of actual wafer state measurements. The previously described issues with robustness to sensor and chamber state drifts apply to these models as well.

Components of multivariate FDC are being enabled by a number of software vendors [7-14] with capabilities for analyzing machine and sensor data. These algorithms still have to be integrated into the data acquisition scheme used in a particular installation, and this is a significantly complex task in itself. But at least the data analysis is facilitated by the availability of such commercial software.

Model Base Process Control

For MBPC, there is a similar trend away from the control of a single wafer state parameter towards multivariate, sensor and model-based process control. This evolution requires:

- sensors for wafer state measurements, if possible (e.g. Full Wafer Interferometry [15])
- "virtual sensors" for parameters that can not be directly measured
- sensor data acquisition, data transfer and communications to a computational algorithm have to be seamlessly automated
- models and control algorithms to be used for control
- a controller that performs these necessary computations
- a feedback loop to the machine, that allows newly calculated recipes to be downloaded to the machine and executed for the next wafer (run-to-run control)

Figure 2 shows an example of a system architecture, generated during the MMST program, that can provide these capabilities. This controller, be it imbedded in the OEM tool or added in a piggyback fashion, has to have capability to perform the multiple major tasks -defined by the boxes in Figure 2 - with a user-friendly GUI, otherwise the

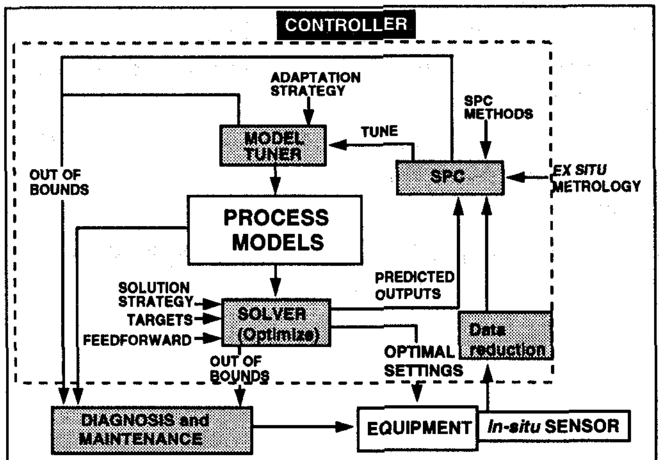

Figure 2. Fundamental components of APC

complexity of the controller will deter its use. The first major issue is data acquisition and reduction. If process state sensors are monitored for APC, the next hurdle is the numerous dimensions to deal with, such as: a large number of parallel signals (significantly increased if looking at spectral data) to be analyzed for within-wafer, wafer-to-wafer, within-lot and lot-to-lot variability. The controller also has to have univariate and multivariate SPC capabilities. Another fundamental requirement for APC is that input/output models be available for the modeling of the sensor readings to the wafer properties or hardware states. Polynomial model generation has become routinely available and utilized for process characterization, but other techniques such as Neural Network modeling are also being investigated. In some cases (e.g. spectroscopic measurements of plasma properties), a key issue becomes the temporal stability of these models, given that measurements are made through optical windows that continually degrade in transmittance as the reactor ages between cleaning cycles. The controller also has to have optimization capabilities so the available control algorithms can act effectively on the process models. Finally, the controller has to be able to communicate back to the processing tool, typically through a SECSII interface, and the tool has to be ready to accept recipe changes generated by this controller.

It is clear, without going into more detail on each component, that APC is a complex system requiring interaction from a multiplicity of technical disciplines and between the tool vendor, the sensor and controller manufacturers and the ultimate Wafer Fab user. But this task is also benefiting for the development of commercial software for executing the components of MBPC [3,16].

In summary, multivariate APC is now a widespread goal that is within the near-term plans for the semiconductor industry. However, in contrast to the early univariate APC activities at TI, multivariate APC can be conceptually rather complex and can be implemented only after a rather significant investment in hardware, software and new operating methods. The complexity of this APC methodology has been an impediment to its dissemination and widespread use. But with all the ongoing activities in semiconductor companies, and the interactive programs with OEM, sensor and controller suppliers through SEMATECH, it is clear that multivariate APC will be implemented in mass production within the next 3-5 years.

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