PROCESS SYSTEMS ENGINEERING (PSE) APPLICATIONS IN INTEGRATED CIRCUIT (IC) MANUFACTURING

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Abstract

The manufacture of integrated circuits is driven by a demand for faster calculation capabilities and lower costs, which will require the development of a new generation of manufacturing tools to increase yield productivity, spearheaded by improved measurement devices and advanced process control and the necessary engineering support. The objectives of this paper are to motivate work in this field through a review of the challenges and the state-of-the-art in two main PSE areas as applied to microelectronics manufacturing: process control and process monitoring. PSE solutions appropriate for these challenges involve harnessing multivariate statistics, automated modeling approaches like genetic programming, and multivariable model-based control. The paper is illustrated with several example applications, including one currently under testing at Tower Semiconductor Ltd., a foundry for integrated circuit manufacturing in Israel.

Keywords

Integrated circuit manufacturing; Process systems engineering; Model-based control; Process monitoring

Introduction

In 2003, worldwide revenues for semiconductor device manufacturing were some $175 billion. The industry invested $72 billion in capital and equipment spending, in preparation for what is expected to be a surge in device demand in 2004. If nothing else that you read in this paper excites you, just keep the following in mind: the potential annual benefit resulting from each percent of yield improvement in semiconductor device manufacturing is $1.7 billion.

Semiconductor devices, usually referred to as integrated circuits (ICs), are created by subjecting wafers of doped silicon to a cycle of processes designed to form layers of conducting, semi-conducting and resistive layers with a prespecified topology, to impart the desired electronic functions on the final device. The production of microelectronic devices in commercial FABs (fabrication facilities) follows one of two alternative streams: single wafer processing (SWP), and the processing of batches of wafers.

The width of polysilicon lines that can be repeatedly attained, defining transistor gates in IC circuits, is the key performance factor, usually referred to as the *design rule*. Technology commonly in use today has the capability of generating topology with design rules of 130 nm (1/300 the thickness of a human hair), based on 200 mm diameter silicon wafers. Furthermore, as pointed out by the international technology roadmap for semiconductors (ITRS) 2003, the IC industry is driving towards the manufacture of more compact devices, based on 300 mm diameter wafers, and even smaller design rules, with 70 nm in ramp at several locations worldwide at this time.

As discussed by Butler and Edgar (1997), these market forces will require the development of a new generation of manufacturing tools, and the necessary engineering support, spearheaded by improved measurement devices and advanced process control. The ITRS also emphasizes the need for metrology as feature sizes continues to shrink. As is well known, metrology accelerates yield improvement and cost reduction at every stage of manufacturing through better characterization of process tools and processes. This is especially true for lithography, which has long accounted for a significant portion of over-all semiconductor manufacturing costs and throughput.

The current practice in the IC industry is to implement open loop, recipe-driven, feedforward control strategies. Often, the desired operating point is determined following a statistical design-of-experiment (DOE) study to define the "stable" process window. Subsequently, the degrees-of-freedom of the process (the manipulated variables) are fixed according to the DOE results. Feedback control, if implemented at all, is usually limited to single loop PID control, and usually only for the lower level loops (e.g., temperature control). The main disadvantages arising from the widely accepted feedforward control strategy are obvious to anyone with modest control experience: (a) the approach cannot deal with unmeasured and/or unknown disturbances (which, of course, always occur in practice), and (b) since the feedforward correction is based of imperfect process knowledge, it will generally not allow product to be produced consistently on target (even in the absence of disturbances). Modeling activity is seldom seen, and if at all, usually limited to empirical, data-driven approaches. Typically, when loss-of-control (LOC) incidents are encountered, the process is stopped, with a resulting loss in yield, and a new DOE is initiated to assess the problem and suggest corrections. Surprisingly, process monitoring is usually carried out using univariate methods, despite the fact that hundreds of variables need to be monitored, often strongly correlated.

Modern PSE methodologies can significantly improve the management of IC manufacturing. These call for model-based approaches, where models are generated with accuracy at a level appropriate to the application. Multivariable feedback control is favored as a means to deal with unmodeled/unmeasured disturbances and to accommodate constraints. Process monitoring is carried out relying on multivariate methods, such as principal component analysis (PCA), coupled with first principles modeling to generate "smart" alarming. Ideally, the monitoring system should be integrated with the regulatory control system, to provide the framework of truly advanced process control (APC).

The objectives of this paper are to present the challenges and the state-of-the-art in two main PSE areas that have application in microelectronics manufacturing: process control and process monitoring, illustrated by example applications developed in cooperation between our research group and the IC industry in Israel.

Application Area 1: Process Monitoring

In the microelectronics industry, attempts are being made to enhance performance and yield via fault detection. Most of the attention is being directed at reducing process variation by various means: feedforward control for reducing run-to-run variation (Ruegsegger et al, 1999), as well as model predictive control (Edgar et al, 1999). Multivariate statistical methods have also been applied with varying degrees of success (e.g., Chen et al, 2000).

In recent work performed in our group (Lachman-Shalem et al, 2002a), a physical model describing an oxidation tube was used to simulate faulty oxidation ovens in the fabrication of a CMOS transistor, and combined with PCA to monitor simulated CMOS manufacturing, in an approach referred to as model-based PCA (MBPCA). Figure 1 shows a typical analysis with MBPCA, where the simulated fault is an increase of 5% in the hydrogen flow into the oven. First noted is the fact that the average oxide thickness measured on the test wafers has increased by about 1% and does not reach alarm limits, and since the change is very small, it may go unnoticed. Using MBPCA for analysis of the same data and calculation of the squared prediction error (SPE), an alarm is immediately raised as the prediction for the oxygen inflow is wrong and its SPE value crosses the alarm limits.

This abnormal event ultimately causes the process to violate its specifications, even though monitoring individual measured variables can be safely within their specific normal bounds. However, multivariate statistical methods such as PCA, especially when combined with physical modeling, have the capacity to identify in addition situations in which the normally occurring correlations between variables are violated. For more details, the reader is referred to Lachman-Shalem et al (2002a).

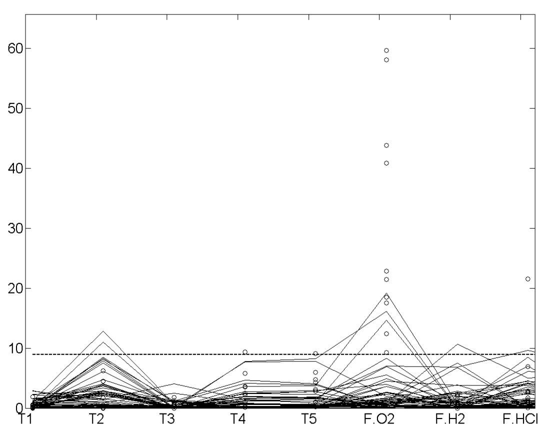

Figure 1. Example performance of MBPCA in failure detection.

Application Area 2: Process Control

Photolithography Control

The microelectronics industry today owes much of its success to remarkable advances in the lithographic process used to fabricate integrated circuits. The economic inducement of cheaper yet more sophisticated integrated circuits continues to motivate the industry to produce ever-smaller features. The miniaturization of the components of the integrated circuit has been achieved through improvements in projection printing, in the photoresists that are used to generate the structures, and better control of the photolithography cluster. The main production problem is the control of the precision of the printed line width (critical dimension, CD).

Much work has been reported on the application of process control to lithography. Lithography is comprised of a number of basic, but interacting, operations. Despite this, to the best of our knowledge, all of the reported work on photolithography control relates to single-loop control, in which a key manipulated variable in the process track is selected for regulation of the specified CD. In theoretical work carried out in our group, a nonlinear model predictive control (NMPC) has been developed and tested on a full-track simulation using the commercial simulator PROLITH. The performance of the NMPC has been demonstrated to be significantly better than the best-possible single-loop controller (Lachman-Shalem et al, 2002b).

The success of the theoretical study provided the motivation to test the NMPC approach on a problematic layer at Tower Semiconductors Ltd. (TSL), an IC foundry in Migdal HaEmek in Israel. The methodology proposed in Lachman-Shalem et al (2002b) was followed, modified to account for FAB limitations, namely: (a) the manipulated variables used for the controller were limited to the stepper variables (dose and focus); (b) Both dense and isolated CDs were regulated; (c) The controller was implemented lot-by-lot, rather than wafer-to-wafer.

Realization of the NMPC approach to the TSL FAB involved the following steps:

(a) Calibration of the PROLITH model using focus exposure matrices (FEMs) supplied by TSL.

(b) Generation of empirical nonlinear models relating the focus and dose to the CD outputs. This was carried out using our in-house genetic program (GP) – see Grosman and Lewin (2002).

(c) Development of NMPC using the nonlinear GP models to predict the process behavior. The controller uses filtered CD measurements, weights to favor the tracking of the more critical dense CD values, and to maintain the manipulated variables in mid-range, whenever possible. Figure 2 shows the simulated performance of the NMPC in rejecting a disturbance in the development time, imposed at sample 0 in the plot. Note that whereas this disturbance causes the uncontrolled dense CD to violate its lower acceptance limit bound, the NMPC succeeds in rejecting the disturbance almost immediately. The simulated noise levels correspond to those found in the FAB.

(d) Implementation at TSL. The pre-tuned controller was implemented successfully with no further adjustments to any of the tuning parameters, giving the performance as shown in Figure 3. The same disturbance simulated in Figure 2 was imposed at wafer 2, causing the dense CD to violate its lower acceptance limit at wafer 6. At this point, the NMPC was activated, returning both dense and isolated CDs to their set points.

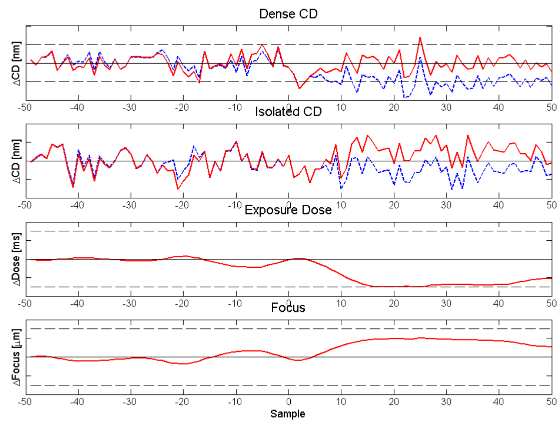

Figure 2. Open-loop (blue dashed) and closed-loop (red full) response of CD dense and isolated lines to a simulated disturbance in development time.

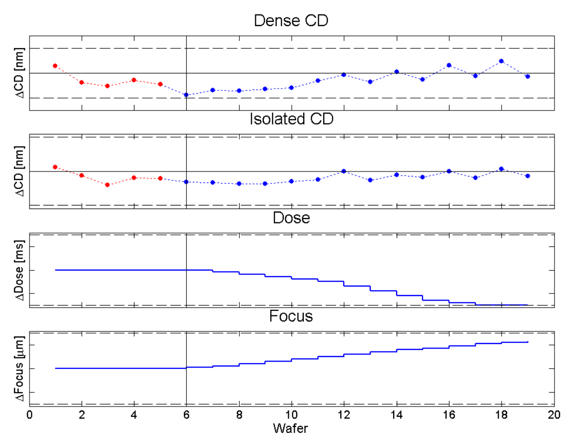

Figure 3. True closed-loop response of CD dense and isolated lines to a disturbance in development time as implemented at TSL.

Note that in both the simulation and in the FAB test, the regulation of the CDs is attained at the expense of having both of the manipulated variables at their constrained limits (the dose at its minimum value and the focus at its maximum value). This is an indication of a process problem (indeed, the development time is excessive), and should be identified by the monitoring system. It is recommended that multivariate statistics be employed in setting up such a system, as discussed above.

Control of Single Wafer Processing (RTP).

Single wafer processing, in wafer-by-wafer batch chambers, focuses on control of temperature and thickness uniformity. Several control techniques have been attempted from decentralized control (Scaper et al, 1999) to hybrid control strategies involving non-conventional approaches such as genetic algorithms and fuzzy logic (Lai and Lin, 1999). In the past few years, Rapid Thermal Processes (RTP) have gained acceptance as mainstream technology for semiconductor manufacturing. In RTP, the main control problem is that of temperature. In work carried out in cooperation with Steag CVD Systems, we developed two alternative approaches for the regulation of temperature uniformity:

(a) A steady-state algorithm involving reverse- engineering of the required power distribution, given a history of past distributions and the resulting temperature profile. This uniformity algorithm is used to set different zone ratios for the process region and for the ramp stage, with set point tracking of the wafer center-point temperature achieved using an IMC-tuned PI controller. By using different zone ratios, the overall temperature uniformity is kept at ± 2 ºC of the set point.

(b) NMPC (Grosman and Lewin, 2002) is implemented for RTP temperature regulation using transient models developed using genetic programming (GP). The strength of this approach is that the same set of tuning parameters can control the RTP system at a range of operating temperature set points with a very short rise time and a uniform, steady-state temperature profile.

Conclusions

The drive for increasingly smaller critical dimensions in IC manufacture, together with increased yields is leading the industry to turn to APC solutions for the monitoring and regulation of production. This paper has focused on the possible impact of PSE tools in IC manufacturing. The three applications demonstrated together indicate that the implementation of model-based, multivariable control, backed up by a smart monitoring system using multivariate statistics, appears to have great promise in many applications.

From our experience, the entry of system engineers into the IC manufacturing business involves a steep learning curve. It is important to have a good working knowledge of the business, its vocabulary and technology, and this requires serious effort. Without this knowledge, communication with partners in the IC industry is difficult, but with it, and the necessary enthusiasm at the receiving end, the expertise and experience brought by the control systems engineer provide vehicles for significant contributions.

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