行政院國家科學委員會補助專題研究計畫成果報告

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計畫主持人：郭瑞祥

共同主持人：陳正剛

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- □赴國外出差或研習心得報告一份
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- □出席國際學術會議心得報告及發表之論文各一份
- □國際合作研究計畫國外研究報告書一份

執行單位：台灣大學工商管理學系

中 華 民 國 90 年 8 月 1 日

行政院國家科學委員會專題研究計畫成果報告

半導體集結式機台整合檢測與控制

Integrated Inspection and Control for Semiconductor Cluster Tools

計畫編號：NSC 89-2218-E-002-055
執行期限：89/8/1 ~ 90/7/31
主持人：郭瑞祥　　台灣大學工商管理學系
共同主持人：陳正剛　　台灣大學工業工程研究所

摘要

本計劃發展整合檢測與控制技術，其中包含了離線製程最佳化技術與線上製程控制技術。藉由整合機台、製程、材料與晶圓的資料收集，決策分析與執行，以改善機台與製程的表現。

在第一年中，我們發展了合理分群技術以建立了快速熱氧化製程之非均勻度統計模型。在第二年中，我們發展了自我調適督導控制技術。

第三年重點為製程整合檢測與控制，具體的工作項目包含了：

1. 發展整合檢測與控制技術
2. 建立整合檢測系統雛型
3. 進行資料分析

目前第三年的目標均已完成，我們已發展了整合檢測與控制技術，並且建立了整合檢測系統雛型。運用時間序列與多變量統計之技術，我們建立了及時機台資料之模型，以作為線上機台監控之用。

關鍵詞：統計製程管制、督導控制、及時機台監控

Abstract

The goals of this three-year project are to develop integrated inspection and control schemes for semiconductor cluster tools, which include off-line process optimization and on-line process control techniques.

In the first year, we have developed rational subgrouping technique for modeling the oxide thickness non-uniformity of the rapid thermal cluster tool. In the second year, we then developed the on-line supervisory control technique.

The tasks of the third year include: 1) to develop integrated inspection and control methodology 2) to construct an integrated inspection system prototype and 3) to conduct data analysis.

Currently the tasks are all completed. The proposed integrated inspection methodology is developed and the equipment monitoring system prototype is constructed. Time-series modeling and multivariate statistics are used to model the real-time equipment data for on-line monitoring purpose.

Keywords: statistical process control, supervisory control, real-time equipment monitoring.

Integrated Inspection and Control for Semiconductor Cluster Tools

ABSTRACT

As the wafer size increases from 200mm to 300mm, quality improvement and control for single wafer processing demand a tighter inspection and automation requirement. In recent years the use of cluster tools has become increasingly important for semiconductor fabrication. It is the goal of this research to develop integrated inspection and control schemes for semiconductor cluster tools, which include off-line process optimization and on-line process control techniques. Key algorithms of the developed techniques are reviewed.

INTRODUCTION

As the wafer size increases from 200mm to 300mm, quality improvement and control for single wafer processing demand a tighter inspection and automation requirement. In addition, to maintain the current productivity improvement in IC fabrication, the overall equipment effectiveness (OEE) must improve from the current 35% to 70% [1]. Studies have shown that process control will contribute to the OEE improvement because 1) it reduces the time for running test wafers 2) it improves wafer output quality 3) it reduces unscheduled downtime 4) it reduces the time for wafer rework and 5) it enhances correction efficiency. In the meantime, there has been a trend toward more in-situ measurements and real-time control for future semiconductor fabrication. This in turn demands an integrated inspection and control solution. It is then the goal of this research to develop integrated inspection and control schemes for semiconductor cluster tools. Here we define process optimization and control as the improvement of equipment / process performance by the integration of equipment, process, material, and wafer information acquisition; decision making; and execution.

In the current practice, process optimization and control are implemented in two stages: off-line and on-line. Off-line optimization uses the techniques of design of experiments [2]. Response surface methods [3][4] and the Taguchi method [5][6] are examples of methodologies based on the design of experiments. Both methods create models for the purpose of estimating the optimal operating point (recipe).

The most popular approach for on-line process control is the use of statistical process control for on-line fault detection [7][8]. Although it has been practiced in the semiconductor industry for many years, its capability is not fully utilized. Two examples are rational subgrouping and sampling techniques. For example, Roes et al. [9] describe the rational subgroup techniques. Nurani et al. [10] and McIntyre et al. [11] investigate the sampling issue within the semiconductor industry. Spanos et al. in UC-Berkeley [12][13] and Bunkofske in IBM [14] propose an SPC scheme that utilizes time-series and multivariate SPC techniques to monitor tool data. Another on-line process control scheme that is getting more attention within the semiconductor industry is the supervisory control or run-to-run control. The SIA roadmap has specifically mentioned that during 1999-2004, run-to-run control should be implemented [15].

In summary, the integrated process control strategies have been identified as [16]:

a) use in-line / in-situ metrology
b) use supervisory control
c) track individual wafers
d) use multivariate SPC methods, and
e) monitor equipment performance in real time.

Based on these requirements, an integrated inspection and control framework for semiconductor equipment is proposed in Figure 1. As can be shown, the proposed framework consists of three modules: SPC, supervisory control and real-time monitoring. The SPC module serves as an on-line post-process monitoring tool while the real-time monitoring module serves as a real-time equipment/process monitoring tool. The supervisory control module serves as a run-to-run control on wafer output quality. Below, we review the key algorithms of each module.

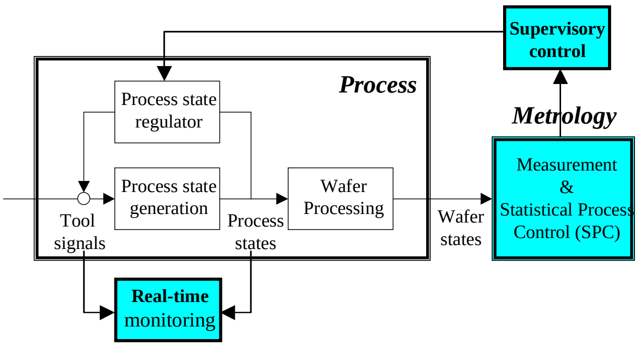

Figure 1: Integrated inspection and control

SPC AND SUPERVISORY CONTROL

Figure 2 illustrates the functional framework of the SPC and supervisory (feedback) control. As can be seen, the SPC module is used to distinguish between the common causes of variations and the special causes of variations. Only when there is an evidence indicating that the abnormal deviation is statistically significant, will the control actions be taken. Here, the Shewhart control chart is used to detect a large process deviation while the EWMA control chart is used to detect a small process deviation. In the supervisory control module, both small and large deviation prediction modules use a moving average formulation. The constant term of a linear control model, initially obtained through off-line design of experiments and regression technique, is then re-tuned based on the estimated process deviation. A new process recipe (equipment setting) for the next run is generated to compensate for the observed process deviation. This detection and control process is then repeated on a run to run basis.

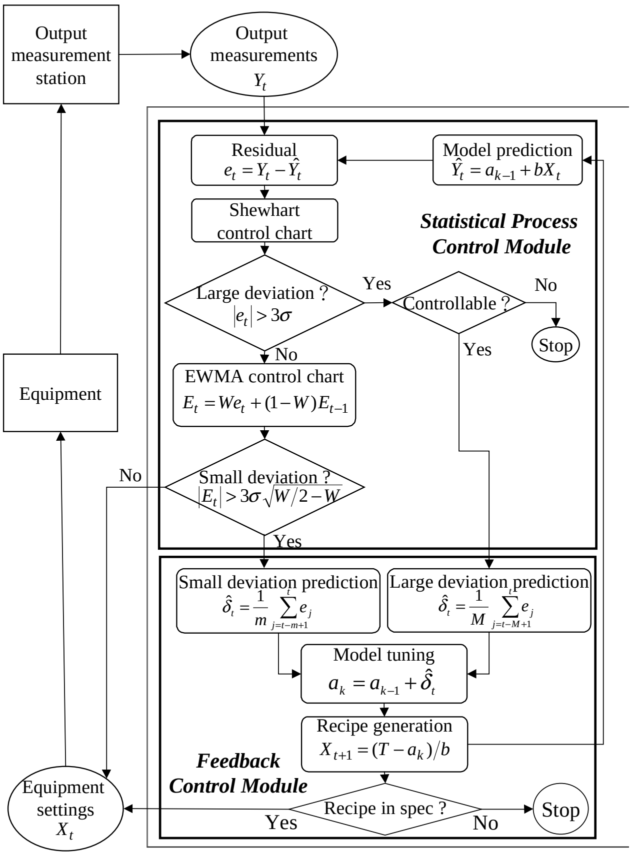

Figure 2: SPC and supervisory (feedback) control

Next we demonstrate the effectiveness of the proposed algorithm through a simulated example. In this simple example, a process is assumed to have the model form as:

$$Y_t = \alpha + \beta X_t + \varepsilon_t \qquad (1)$$

in which α = 3000, β = 10 and $\varepsilon_t \sim N(0, \sigma^2)$, σ = 50. Let's further assume the target output is 3500. Now suppose that the process mean has a sudden shift of 3σ at run 10 and the results of the process output with and without using the detection and control algorithm are compared in Figures 3(a), 3(b) and 3(c). As can be seen, the process is brought back to the target value in two adjustments that occur at runs 13 and 27. The first adjustment at run 13 is actually triggered by the Shewhart control chart at run 12 and the adjustment magnitude is around 1.89σ. Since it is not completely compensated, there is another adjustment at run 27 which is triggered by the EWMA control chart at run 26 and the adjustment magnitude is around 1.15σ.

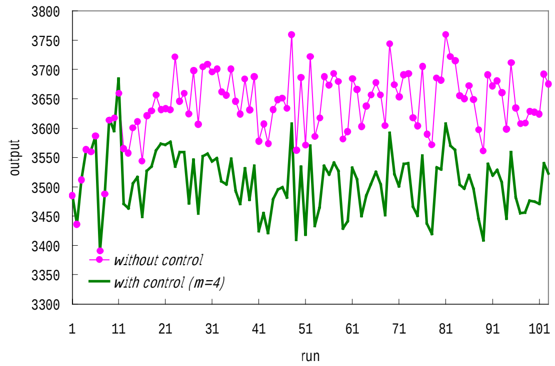

Figure 3(a): A simple example to show the effectiveness of the proposed detection and control algorithm.

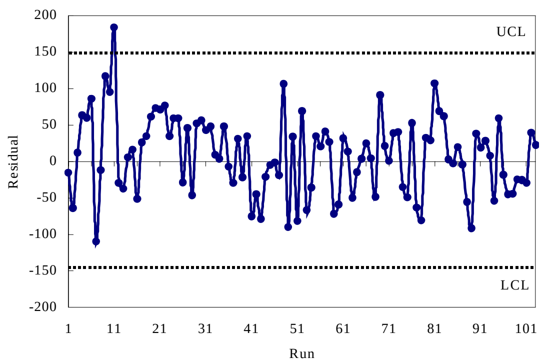

Figure 3(b): Shewhart control chart for the simulated shifting process.

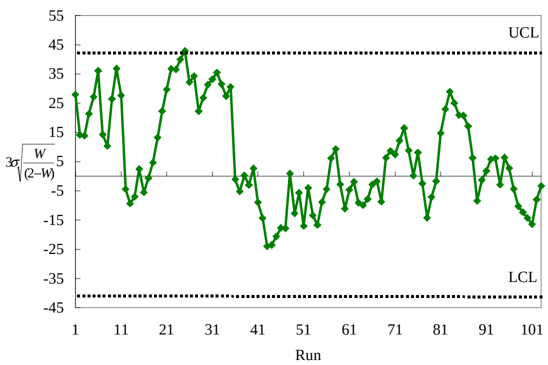

Figure 3(c): EWMA control chart for the simulated shifting process.

REAL-TIME MONITORING

Real-time equipment monitoring and fault detection become critical as most problems reveal themselves first on the equipment performance and much later on the wafer quality. To perform real-time monitoring, we have proposed the following generic functions as shown in Figure 4.

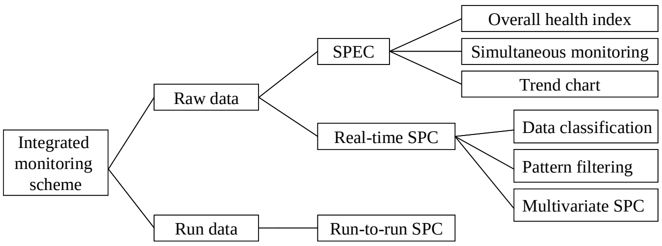

Figure 4: Generic functions in real-time monitoring.

As can be seen, the raw data can be examined through the pre-determined specification windows. In this respect, we propose the following functions:

a) Overall health index: This index provides an overall evaluation of the equipment's health. Based on evaluation of the tool parameters' performance against the setting specifications, a score is calculated. The score is re-evaluated when new sampled data points are received.

b) Simultaneous monitoring scheme: The scheme consists of 3 concentric circular regions. Observations of different parameters are first normalized and then displayed simultaneously on a dartboard. The farther away the observations from the dartboard center, the worse the performance of the corresponding tool parameters. The display of the scheme provides an easy reading of the equipment's overall status.

c) Trend analyses: The trend charts will help us to examine the equipment performance over time.

Based on the proposed functions, a prototype is developed using the data from a single-wafer rapid thermal chamber (Figure 5). Figure 6 and 7 show the overall health index, simultaneous monitoring dartboard and trend analysis for the rapid-thermal chamber.

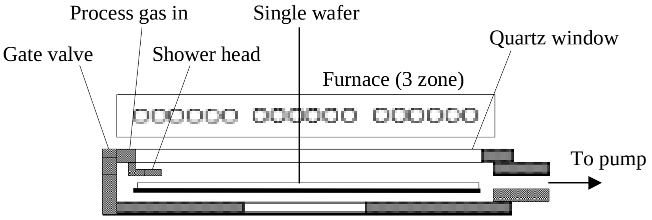

Figure 5: Single-wafer rapid thermal chamber.

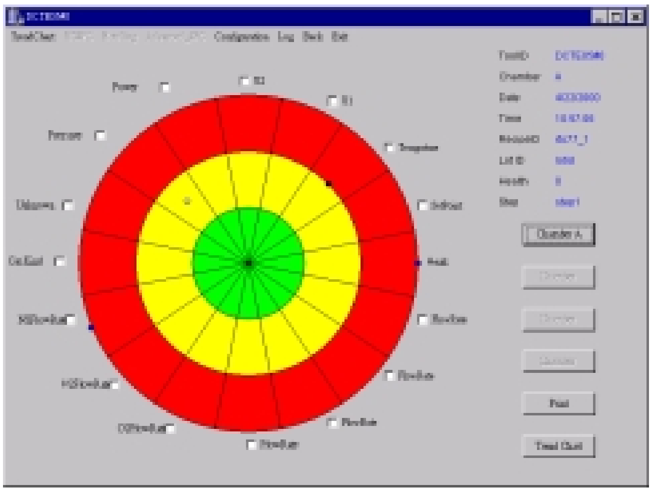

Figure 6: Overall health index and simultaneous monitoring for the rapid thermal chamber.

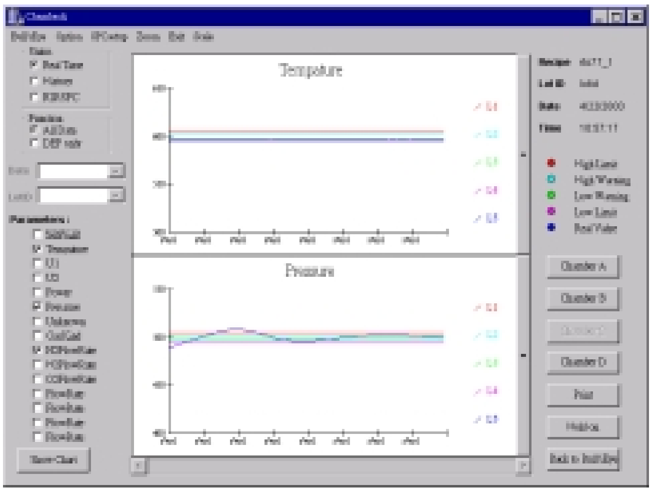

Figure 7: Trend analysis for the rapid thermal chamber.

Because of the presence of process dynamics and internal feedback control mechanism, the real-time raw data often possess auto-correlation and cross-correlation natures. This prevents us from directly applying the traditional SPC techniques to the real-time data. Pre-treatment of raw data is thus needed. With data items classified into independent groups, the following functions are proposed for the real-time statistical monitoring:

a) Pattern filtering: This function builds a mathematical model to characterize the equipment behavior based on equipment data collected in real-time. Such a model allows us to predict the running trend of each data item under in-control conditions. By subtracting the predicted values from the actual observed value, the running pattern of the equipment data is filtered out. Left over is the residuals that can be later used to detect faults caused by special causes.

b) Multivariate SPC: The multivariate SPC technique is applied to the residuals of multiple data items to detect special faults that cause the process excursion. With the pattern filtering function described earlier, the normal behavior of the equipment data has been correctly predicted. If any excursion occurs, the actual observed values will deviate from the predicted values and the excursion will manifest itself in the residuals' deviations.

Figure 8 shows the correlation between two equipment signals while Figure 9 shows the data pattern filtering function applied to the monitored signals.

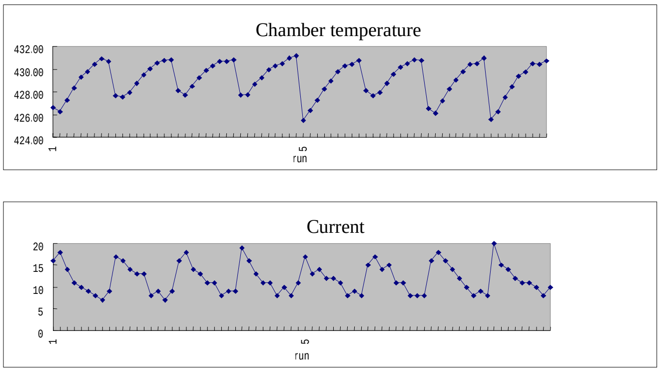

Figure 8: Correlation between temperature and current.

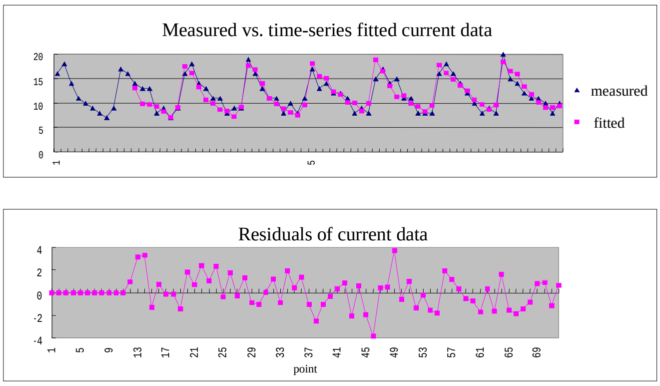

Figure 9: Data pattern filtering.

CONCLUSIONS

In this research, we have presented an integrated inspection and control scheme for semiconductor cluster tool. It consists of three modules of SPC, supervisory control and real-time monitoring. The SPC module and the supervisory control module provide an on-line run-to-run process quality control capability. The real-time monitoring module provides real-time equipment/process monitoring function. Generic functions and modeling algorithms were developed and a prototype was constructed to demonstrate its feasibility.

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