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The objective of this DARPA research project was to develop real-time control systems using in-situ sensors for semiconductor manufacturing. Our initial application was the development of a temperature control system for Rapid Thermal Processing (RTP) equipment. We developed mathematical models of RTP, analyzed them, identified and validated these models, deduced several control algorithms and finally applied them to real systems at Stanford University and at Texas Instruments. Also, based on our analysis, we modified the design of the system hardware (lamp array) and also proposed an optimal lamp array design technique.

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Multivariable Control for Flexible IC Processing

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Multivariable Control for Flexible IC Processing

DARPA Project, January 1, 1990 – September 30, 1992

Executive Summary
(T. Kailath and C. Schaper)

1 Project Description

The objective of this DARPA research project was to develop real-time control systems using in-situ sensors for semiconductor manufacturing. Our initial application was the development of a temperature control system for Rapid Thermal Processing (RTP) equipment. We developed mathematical models of RTP, analyzed them, identified and validated these models, deduced several control algorithms and finally applied them to real systems at Stanford University and at Texas Instruments. Also, based on our analysis, we modified the design of the system hardware (lamp array) and also proposed an optimal lamp array design technique.

2 Outline of Results

Our approach began by analyzing the performance limits of available RTP equipment using detailed physical models [1]. It was evident from these studies that multivariable actuation (i.e. multiple independently controllable lamps) was needed in order to achieve uniform and slip-free processing.

We then developed modeling strategies to characterize the temperature dynamics in Rapid Thermal Processing (RTP) systems with multiple independently controllable lamps.

Two approaches were investigated in the development of the models. The first method [2] viewed the RTP system as a black-box. A mathematical model of the temperature effects for this representation was determined by exciting the inputs (lamp powers) and measuring the outputs (thermocouples or pyrometer measurements). A dynamic linear model of the system was then determined by correlating the inputs against the outputs. To automatically identify this correlation for RTP systems, a

novel technique was developed and tested. This technique employed signal processing ideas from newly developed high-resolution sensor array processing theory that have the advantage of processing large quantities of data quickly (relative to alternative approaches). In order to handle the nonlinear characteristics of RTP due to radiative heating, multiple linear models were obtained at different operating points. Then, a Linear Quadratic Gaussian (LQG) controller combined with convex optimization techniques was designed for these linear models and successfully applied to the experimental RTP system at Stanford University [3], [4].

The second approach employed a joint mathematical/physics-based approach [5], [6]. In this technique, a physical model of RTP was derived. The model incorporated actuator and sensor dynamics as well as the wafer heating dynamics. Thus, the model captured the nonlinear effects of RTP. However, the physics-based model contained parameters that could not be accurately determined from first principles. Consequently, experimental data was obtained from the RTP equipment by exciting the lamp powers and measuring temperature. This data was then optimally fitted to the parameters in the nonlinear model structure suggested by the physical derivation. We then developed a real-time controller for such models. The controller used a global-model based predictor to track the desired temperature trajectory and a local-model based feedback compensation mechanism to correct for disturbances and modeling errors. This temperature control strategy was successfully applied on a variety of significantly different RTP equipments.

Our control strategy was first verified on the Stanford RTP system which employs a three- zone lamp, three-point thermo-couple (t/c) sensor for four-inch wafers. Next, the control strategy was transferred and applied to the Advanced Vacuum Processors (AVPs) at Texas Instruments (TI) in Dallas for the following equipment configurations: four-zone TI lamps and six-zone G-squared lamps, four-point t/c sensors, six-inch wafers, and a TI chamber/showerhead arrangement. The control system was tested on silicide react, silicide anneal, and tank anneal process cycles. Work is continuing at TI to evaluate the temperature controller on additional processes, to integrate it with noninvasive temperature sensors, and to incorporate it into the CIM environment.

Besides the design of real-time model-based control systems, these models were employed in designing an Extended Kalman Filter to reduce measurement bias and

noise in pyrometry. Our approach is based on reconciling the model behavior and the measurements. This technique has been studied through simulation and promises to improve pyrometric measurements in the presence of emissivity variations. Another byproduct of our modeling studies, is an optimal design of lamp arrays in RTP systems [7]. Experimental validation of this method remains to be done.

Modern control theory also offers other opportunities to greatly improve the quality and reproducibility of semiconductor processes. We addressed the computer software and hardware implementational issues for real-time control of semiconductor equipment and processes, by taking an approach based on the theory of discrete event systems. The main advantage of this theory for manufacturing applications is that multitasking computer programs can be synthesized or updated quickly and reliably when either new recipes are requested or new equipment is added. Our accomplishments to date include a novel multitasking software environment that is developed for manufacturing processes in general and was applied to the Rapid Thermal Multiprocessor (RTM) at Stanford. In addition, the discrete event approach has been developed in a hybridized framework that incorporates real-time dynamic control. This work is one of the first to apply this theory and framework to a manufacturing process [8]. Again, the computer software was successfully transferred to TI.

3 Applications in Lithography

Though the original program only envisaged use of signal processing ideas only in so far as they were appropriate for model identification and control (see [2], [8], [7]), it became clear to us that these ideas could be useful in a much broader range of problems in semiconductor manufacturing. These applications are the major focus of another recently initiated DARPA effort, but some preliminary results may be noted here. We focused our initial investigations in the area of lithography. Here new methods are being developed to improve the capabilities of optical confocal and correlation microscopes to measure the dimensions of features on semiconductor wafers. These measurements can then be used to monitor and eventually control the lithography process. Furthermore, the algorithms are general and have the potential for many applications in machine vision besides lithography including robotic vision [9], [10], [11], [12], [13]. We also investigated image processing techniques for automated de-

fect inspection [14]. In addition, a new computational technique is being developed to systematically design phase-shifting masks for arbitrary integrated circuit geometries. These masks can improve the resolution of photolithography without renovation of current optical exposure systems [15]. Previously, design techniques of phase-shifting masks were heuristic and limited to very simple patterns. Initial designs using the new technique have been developed for the three patterns of most interest: a contact hole, a single space, and periodic lines/spaces [15].

4 Summary

This project has initiated the task of applying the ideas of modern control, optimization, computation and signal processing theories to important areas of semiconductor manufacturing. The results have demonstrated that modern systems point of view can significantly improve current methodologies used in the fabrication of integrated circuits.

Our work suggests the following general comments:

- Real-time control and sensing can be very useful to the semiconductor industry for improving yields and reducing time-to-market. This approach should complement the Statistical Process Control (SPC) concept of run-to-run control.
- Simultaneous coordination of equipment design, control, and sensor technologies is required to achieve this goal.
- Sensing, which is essential to control, is a major problem in the IC industry for several reasons, including noninvasive sensing requirements, submicron features, and processing complexity. Nonetheless, this challenge can be met by using advanced signal processing algorithms, *e.g.*, to reduce the accuracy burden on the sensor itself.
- Consolidation of physics-based and mathematical-based modeling concepts are needed to improve prediction/extrapolation for process control and process synthesis.

- Extension and practical reduction of existing control theory is needed to address specific concerns of the IC manufacturing industry such as reproducibility and uniformity.
- A lot more work can profitably be done along these lines, not just for the semiconductor industry but for advanced materials processing in general.

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Ph.D. Thesis Abstracts

January 1, 1990 – September 30, 1992

S.A. Norman: Wafer Temperature Control in Rapid Thermal Processing

Abstract: Rapid thermal processing (RTP) is a term used for a number of proposed thermal processes in the manufacture of integrated circuits. In RTP wafers are processed quickly, one at a time in a small oven; the heat source is visible and/or infrared radiation from a lamp array. RTP has process-related and economic advantages over conventional batch thermal processing in tube furnaces. During thermal processing of semiconductor wafers it is essential that the wafer temperature closely follows a pre-specified temperature trajectory and that the temperature profile across the wafer is nearly uniform whenever the wafer is at high temperatures. Ensuring adequate wafer temperature control is more difficult for RTP systems than for conventional batch thermal processing systems. Without adequate wafer temperature control, RTP can not be used in mainstream integrated circuit fabrication.

This thesis considers the problem of controlling axisymmetric RTP systems with multiple independently-controllable lamps. In such systems the relative lamp power settings can be adjusted so that the lamps provide a range of distributions of power over the wafer; this is useful because the ideal distribution of incident energy varies according to processing conditions and changes substantially during a single process cycle.

In the thesis numerical techniques are developed for using a thermal model of RTP to optimize performance of axisymmetric RTP temperature control configurations. In particular, techniques are introduced for minimizing temperature error across the wafer during steady-state hold, minimizing temperature error across the wafer during trajectory-following, and determining optimal rejection of static disturbances with a linear feedback error controller and a fixed sensor configuration. These techniques are based on convex optimization, which means that solutions reached by optimization algorithms are guaranteed to be globally optimal and can be used to determine limits of system performance.

The optimization techniques are used in studies using detailed models of hypothetical RTP systems. The results of the studies support important conclusions: that multi-actuator control is capable of providing much better temperature uniformity than single-actuator control and that limits-of-performance analysis is valuable because optimal performance is sensitive to changes in lamp and sensor configurations.

G. Hoffmann: Discrete Event System Theory Applied To Manufacturing

Abstract: High sophistication and sensitivity to changes in a manufacturing system can only be achieved by a complex scheduling and real-time control system. The high complexity of a real-time control system renders it very prone to programming errors. A minor change in the precise timing or scheduling of interactions between parallel components leads to radically different behaviors. Because of a lack of appropriate real-time multitasking software design tools it is difficult to develop reliable multitasking control systems.

The proposed solution is to model and analyze a complex system in the supervisory control framework introduced by Ramadge and Wonham. The possible executions of the system to be controlled and its processing specification are modeled mathematically. The theory provides algorithms for the automatic synthesis of event disabling supervisors from their specifications. This thesis extends the basic supervisory control framework to make it more suitable for the real-time control of manufacturing systems.

A theoretical extension is the explicit introduction of real-time into the basic model. Most previous research focused on the ordering of events and abstracted their occurrence times away. In manufacturing systems, processing must typically be achieved within certain time windows if it is to be acceptable. The thesis extends the results of the basic theory to a timed supervisory control theory. It is shown that the timed synthesis problem can be solved in time polynomial in the number of system states, but exponential in the timing information.

Another relevant theoretical contribution is the introduction of an input-output semantics instead of the disabling semantics. The input-output controller synthesis problems for both an untimed and a timed plant are reduced to forms of the basic supervisor synthesis problem.

An implementation of the untimed synthesis algorithm, to which all considered synthesis problems can be reduced, is proposed. It is based on a data-structure known as Binary Decision Diagram (BDD). This compact symbolic representation method avoids the explicit enumeration of the entire discrete state-space. Its efficiency is demonstrated by a case-study of considerable size.

We also propose a general-purpose discrete event scheduler architecture for the sequential control of manufacturing systems. The scheduler is composed of a disabling supervisor, and of an input-output controller. Both devices enforce different types of specifications.

This thesis was motivated and strongly influenced by a semiconductor manufacturing multitasking control environment developed at the Stanford Center for Integrated Systems. Certain aspects discussed in this thesis have been implemented and tested for this environment.

V. Balakrishnan: Global Optimization in Control System Analysis and Design

Abstract: Many problems in control system analysis and design can be posed in a setting where a linear system is affected by unspecified parameters that lie between given upper and lower bounds. Except for a few special cases, the computation of many quantities of interest for such systems can be performed only through an exhaustive search in parameter space (which is a rectangle in our case).

Branch and bound algorithms provide one way of implementing this search for the global optimum in a systematic manner. These algorithms rely on easily computable upper and lower bounds for the global optimum over any parameter rectangle. First, upper and lower bounds are computed over the original parameter rectangle. These bounds are further refined by breaking up the parameter rectangle into sub-rectangles ("branching") to derive bounds for the global optimum over the original rectangle ("bounding"). The branching is done based on some heuristic rules. As they progress, branch and bound algorithms maintain upper and lower bounds for the global optimum; thus termination at any time yields guaranteed bounds for the optimum.

In this thesis, we describe a simple branch and bound algorithm for global optimization and prove its convergence. We then apply it towards the computation of several quantities (worst- and best-case state decay rate and worst- and best-case norms) that arise in the analysis and design of parameter-dependent linear systems.

List of Presentations

October 1, 1991 – September 30, 1992

- Young Man Cho,
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North Carolina State Univ., Raleigh, NC, April 30, 1992.
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