Improving Vertical Furnace Performance Using Model-Based Temperature Control

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Abstract *- The goal of this project encompasses the design, development, and implementation of a model-based temperature control (MBTC) system to improve the capability of a vertical furnace in a production environment. The approach integrates thermal dynamic modeling of the furnace with robust* H_∞ *multivariable controller design to replace older PID control systems while enabling easy conversion within a manufacturing environment. Initial evaluation of the design utilized an oxidation furnace with the greatest process demands in the given production facility. Results demonstrated excellent steady-state temperature control, virtually no overshoot, and improved run-to-run process uniformity. Cycle time reduction has also been realized by maximizing the temperature ramp rate capabilities and minimizing the temperature stabilization time after ramp completion. These improvements coupled with the elimination of a previously required profiling function significantly increased tool utilization and wafer throughput.*

1 INTRODUCTION AND PROBLEM DEFINITION

One of the process steps in semiconductor manufacturing requires the elevation of silicon substrate to a sufficient temperature to accomplish the diffusion of a dopant or oxidation on the surface. Advances within the industry push towards smaller device geometries that demand equipment with the capability to produce more uniform films, oxides, and dopant concentrations. These advances require improved temperature control sensitivity without long periods of equipment downtime for open-loop parameter tuning.

The equipment of interest in this paper is a vertical diffusion furnace, shown by Figure 1. In a quick description, the vertical furnaces contain a one-to-two meter long cylindrical shaped heating element. The heating element contains either three or five heating zones with each zone having an independent power source used to control the temperature. The heating element has an internal lining of either a quartz or silicon carbide tube supplying accommodations for the silicon wafers. The tube diameter varies depending upon the diameter of the wafers. Each furnace can process from twenty-five to one hundred seventy-six wafers at a time with wafer diameters ranging from 150 to 300 millimeters. Two sets of thermocouples provide the temperature information for each zone, one set located inside the tube and referred to as "profiles", and one set located near the heating element and referred to as "spikes". The profile thermocouples read the temperatures close to the wafers, while the spike thermocouples read the temperatures close to the element.

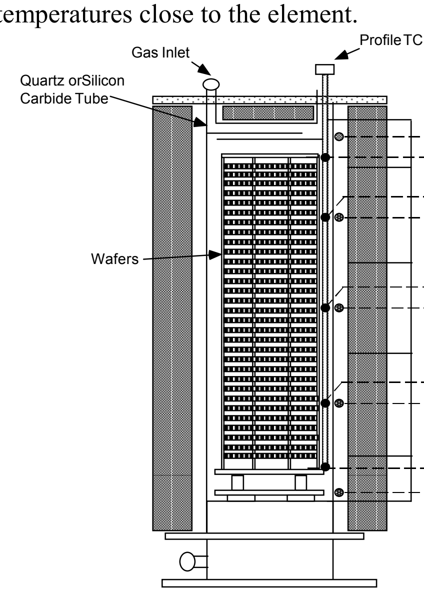

Figure 1. Schematic of a typical vertical furnace displaying the location of profile and spike thermocouples in relation to the heating element and wafers.

The process running in these furnaces can vary significantly, but follow similar basic steps. The steps include the starting of the process run at an idle temperature followed by the loading of the silicon wafers. The furnace, containing the wafers, then heats up for an oxidation, anneal, diffusion, or

CVD process[1]. The process requires specific gas flows reacting at an optimal temperature for a given amount of time. Once the processing step concludes, the furnace cools back to an idle temperature and the wafers are unloaded.

The industry standard temperature controller for the vertical furnace described above employs a proportional integral derivative (PID) algorithm to determine the power applied to each zone of the element. Each term within the algorithm is a function of the error between the thermocouple measurements and the desired control setpoint. The proportional term acts as a primary negative feedback on the measured error. The integral term reduces steady-state offsets on the measured error. The derivative term controls the speed of the response. Performance optimization of the standard PID controller involves manual tuning of the parameters (weights) multiplying the three terms described. The time required for trial-and-error tuning can become very long, resulting in significant downtime for the furnace.

The standard PID controller for the vertical furnace controls the programmed setpoint value to the spike thermocouple reading. Since the desired control parameter is the product wafer, extra functionality is needed for this controller. A periodic profiling function is required to learn the steady-state offset between the profile and spike thermocouple readings. This profiling function determines the necessary control setpoint for the spike thermocouple temperature to obtain the desired profile temperature.

The PID controller, even though it is simple, works surprisingly well when the dynamics of the system are essentially first order and works well-enough for processes where the dominant dynamics are of the second order. However, if the demands on the performance of the controller become too high, then the system requires a more sophisticated controller [1].

The goals for this project include design, development, and implementation of a model-based temperature control system for a vertical furnace to improve the system capability. In addition to the improved temperature control sensitivity, the project must also provide a quick conversion to the production environment without long periods of downtime for the furnace.

[1] Certain processing temperatures are low enough to load and unload the wafers without adding stress to the wafers. For these processes, the idle and processing temperature are equal, eliminating the heating and cooling steps.

This paper describes the results of a partnership between Motorola's MOS 21 fab and Semy Engineering to replace the existing PID controllers. This project includes the development of an integrated furnace identification process and multivariable dual-loop H_∞ temperature controller design. The controller provides increased furnace capability while maintaining ease of use within the fab environment. This paper describes the results of the testing along with improved process results as compared to the previous PID system.

2 DESIGN AND IMPLEMENTATION

A model-based controller utilizes a model of the given system to describe the behavior of the target parameter. The model of the system provides guidelines for the design of the controller used on the parameter. For the application of the model-based temperature controller, the system represents the furnace temperature response to changes in power. This section of the paper describes the design used to achieve the goals for the project and discusses the implementation and testing on a vertical furnace.

The entire design for the MBTC includes the development of a procedure to collect data on the thermal characteristics of the furnace, the tools to translate the thermal characteristics into a model and design a controller, and the means to implement the designed controller. Since performing multiple tests and iterations of the controller design on the target furnace would require large amounts of time and money, the design procedure should require as little experimentation as possible. The development and implementation of a controller design methodology meeting these requirements follow.

The design of an experiment to collect the thermal characteristics requires an excitation of the system that is large enough to allow for the reliable identification of its parameters. The experiment also requires the determination of some robustness measures so that the controller could operate with different system configurations while having a minimal affect on the manufacturing environment. For these reasons, a simple controller is used to control the system under a pseudo-random binary sequence (PRBS) excitation. The PRBS excites the furnace in a pulsed manner at the setpoint command while recording the resulting control inputs (powers) and outputs (furnace temperatures). The data collected from the PRBS provides an indication of the thermal characteristics while minimizing the required equipment use time during the experiment.

After finishing the PRBS, the data is fit with a linear dynamical model, approximating the furnace behavior at the given operating condition. For the approximation, a least-squares algorithm is used to estimate the parameters of the linear model. A weighted version of the least-squares algorithm is used to emphasize the fit of the plant characteristics around the intended closed-loop bandwidth, while regularization is employed to improve the numerical stability of the algorithm [2]. The approximation may require some computer iterations to adjust the fitting weights, but it rarely requires a repetition of the experiment.

The next step in the system identification is the estimation of uncertainty bounds, or confidence limits. The uncertainty bounds can be described as constraints on the achievable performance of the system with respect to controller stability. A violation of these limits can result in poor actual performance and possible controller instability.

After the completion of the system identification, the controller for the system is created using an H_∞ design approach. The uncertainty bounds obtained during the system identification are used to define the controller specifications, in terms of the sensitivity and complementary sensitivity [3]. The sensitivity of the system defines how the output disturbances affect the output of the system. The complimentary sensitivity defines how the measurement noise (and reference input) affects the output. These two specifications define a target loop. The design of the controller then consists of using loop-shaping technique to match the actual closed-loop system with the target.

The final design step is a validation of the controller against the furnace model and assuming a temperature control trajectory to simulate the controller response on the system. The simulation establishes the controller functionality and limitations under temperature ramp conditions and during a forced disturbance on the system.

Once the controller is validated, it is installed on hardware specifically designed to interface to the vertical furnace. The entire installation requires from four to eight hours to install the hardware, execute the PRBS, and download the controller. Thus, the production fab experiences a minimal downtime for the equipment.

The initial evaluation of the design utilizes a five zone vertical furnace processing eight inch wafers. The furnace is tested under a stringent production environment to verify functionality as well as manufacturing reliability. The test furnace produces oxide growths of 200, 250, 500, 600, and 700 Angstroms. The testing includes a comparison of the standard PID controller to the MBTC controller on the same furnace, running the same processes. The goal of the results is to display the temperature responses, including end of ramp sequences, and also display run-to-run measurement results.

3 RESULTS

Many factors determine the capability of a vertical diffusion furnace. However, the most important exists within the ability of the furnace to produce uniform oxidation, diffusion, or deposition on the wafers. Each of these factors strongly depends on temperature control for accurate and repeatable results. In addition to a more uniform oxidation, diffusion, or deposition, a repeatable temperature response can utilize shorter stabilization times during a process, allowing for increased throughput. The quantitative assessment of these factors in relation to the temperature control with the standard PID and MBTC controllers follow. Tests demonstrate the MBTC produces a more accurate temperature response throughout entire processes, including temperature ramps and at steady state. The tests also demonstrate the process results from MBTC controlled processes have a more uniform oxidation growth, leading to increased Cp and Cpk values. Finally, the accurate temperature control resulting from the MBTC allows for a significant reduction in required time for ramps and stabilization, decreasing process cycle time. The following section describes the results of the improvement obtained with the MBTC in comparison to the standard PID controller.

Temperature Response

The temperature response for a vertical diffusion furnace must have accurately controlled temperature ramps in addition to stable processing temperatures. The controller must minimize overshoot after ramps while eliminating oscillations around the temperature setpoint.

For the temperature response test, an oxidation process is considered, ramping from 650°C to 900°C[2]. The temperatures then free-fall back to 650°C once the process completes. Note that the ramp down is not controlled as the natural cooling of the furnace minimizes process cycle time. Figures 2 and 3, illustrate the control of the five

[2] The temperature change is described for the center zone only. The outer zones may have a different target temperature as temperature tilting is used to maximize across load uniformity.

temperature zones during the entire process for the PID and the MBTC controllers. The plots display the profile thermocouple readings since they represent temperatures closest to the wafers.

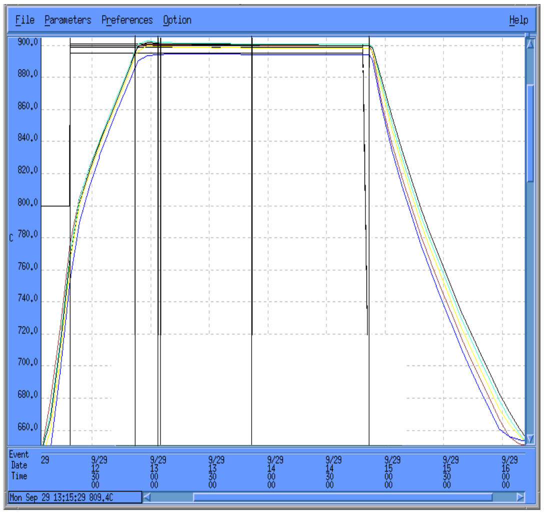

Figure 2. Oxidation process as controlled by the standard PID controller.

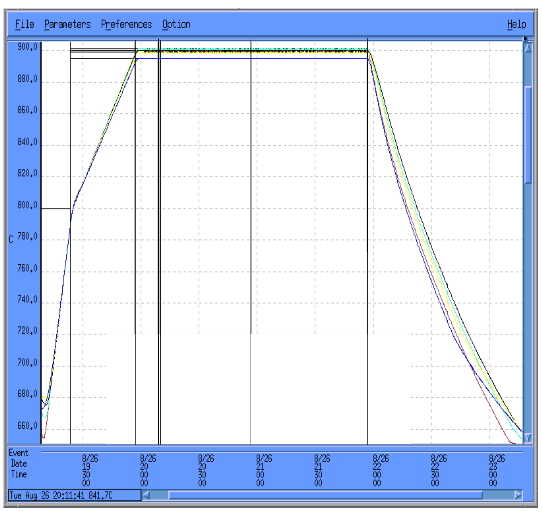

Figure 3. Oxidation process as controlled by the MBTC, displaying improved zone uniformity throughout the entire process.

The MBTC controller holds all five temperature zones close together throughout the entire process, with the exception of the desired temperature tilt around 900°C where the outer zones control to different setpoints. On the other hand, the PID controller cannot maintain a tight control during the ramp. As a consequence, the PID controller has more difficulty stabilizing upon the completion of ramp as compared to the MBTC controller, as shown by Figures 4 and 5.

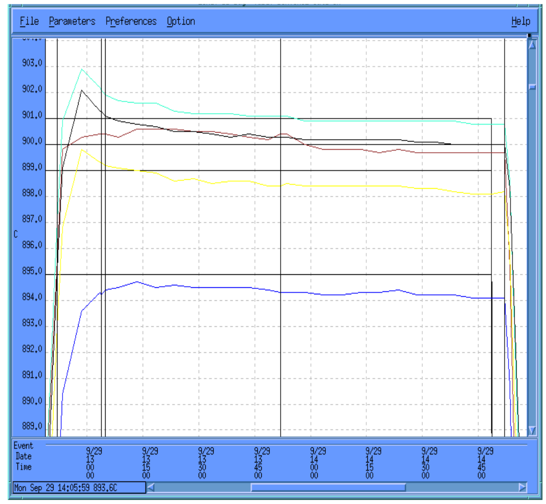

Figure 4. Detailed view of the top of the temperature ramp from figure 2, PID controller.

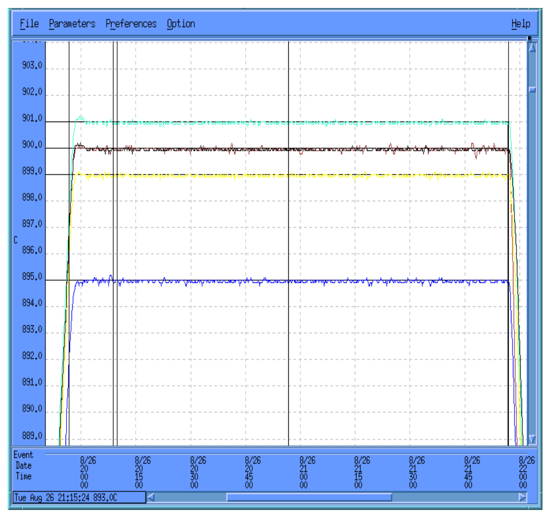

Figure 5. Detailed view of the top of the temperature ramp from figure 3, MBTC controller. The overshoot is virtually eliminated and the steady state control remains within ±0.1°C during the entire process.

A comparison of the PID and MBTC controllers using the same process, shows that the MBTC controller exhibits less temperature overshoot and provides more accurate steady-state temperature control. After a series of process runs, calculations were done to determine control performance. Table 1 summarizes the observed control performance, demonstrating the improvement gained by using the MBTC system.

Control Specification	PID Controller	MBTC Controller
Overshoot after ramp	< 5.0 °C	< 0.3 °C
Ramp settling time	5-20 min.	2-5 min.
Steady-state control	± 0.3 °C	± 0.1°C
Temperature ramp overlap	± 5.0 °C	± 0.2 °C
Run-to-run repeatability	± 3.0 °C	± 0.1 °C

Table 1. Observed temperature control for the standard PID and MBTC controllers.

Measured Process Results

The ability of the vertical furnace to produce a uniform product on the wafer determines the capability of the furnace. Currently, the industry practices the use of placing test wafers in multiple positions across the wafer load of the furnace during each production run to estimate the uniformity for the oxidation, diffusion, or deposition during the run. While the test wafers typically provide five locations of measurement (top, top-center, center, bottom-center, and bottom), the mean of these values is used as a measure of the process uniformity across the load.

The goal for the controller is to maintain the measured process results around the process target. As a standard, the terms Cp and Cpk are used to describe the product results in comparison to the target. The process capability index, Cp, describes the spread of the test measurements as compared to the process limits. The term Cpk represents the location index with regard to the process target. A higher value for each index indicates better performance.

This testing compares the process output from the standard PID controller to the MBTC for several targets ranging from 200 to 700 Angstroms in thickness. The results, listed in Charts 1 and 2, indicate an improvement of the Cp for each process, ranging from a 5% to over 200% increase. Likewise, the results also show an improvement of the Cpk values with an increase of 20% to 140%. The variation in the results indicates that temperature may not be the only factor affecting process uniformity. However, by reducing the temperature variability, it becomes possible to investigate secondary factors affecting process results that were previously overshadowed by temperature control problems.

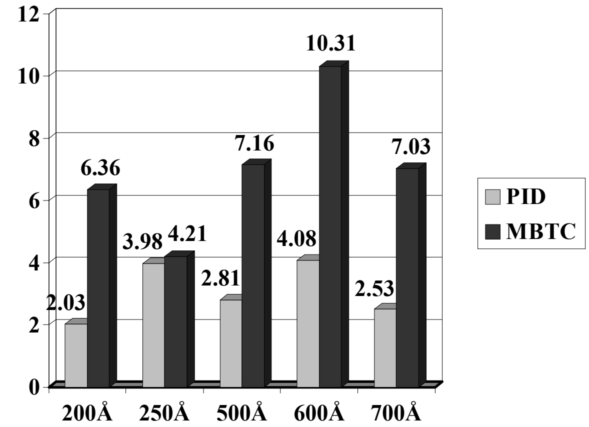

Chart 1. Controller comparison of the process capability index (Cp) for each process.

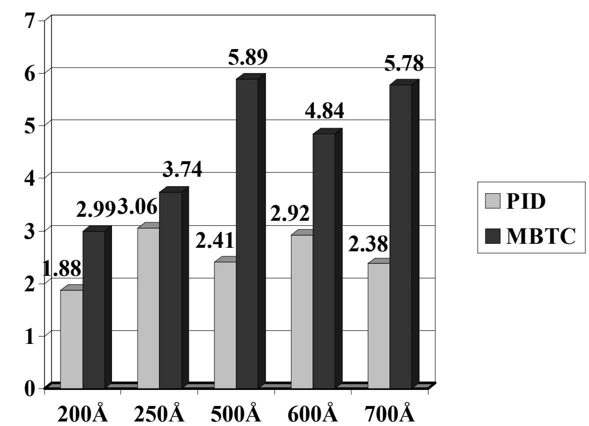

Chart 2. Controller comparison of the location index (Cpk) for each process.

Process Cycle Time

While the uniformity of the process results remains the most important aspect in the determination of the capability of a furnace, the product throughput follows close behind. Improvements in temperature control lead to an increase in the number of wafers a furnace can process uniformly, and thus, the value of the furnace increases. The improvement in temperature response with the MBTC also allows for an increase of the controlled temperature ramp-rate while the required stabilization time following the temperature ramp decreases. These two factors can significantly reduce the total process time as shown by Figures 6 and 7. This test did not require changes to the actual process step within the recipe. Instead, the test demonstrates the minimal time required to reach identical process conditions for both controllers. As shown in Table 2, the standard PID controller requires 92 minutes to reach the processing conditions. The MBTC controller, however, only requires 47 minutes, or 49% less time, to reach the identical processing conditions. For the standard PID controller, any further reduction in the stabilization time may cause product degradation. Thus, the MBTC controller not only improves the temperature response and process uniformity, it also improves the process cycle time of the vertical furnace. However, it should be emphasized that the amount of improvement in processing time, obtained with MBTC, depends on the particular furnace and the processing recipe.

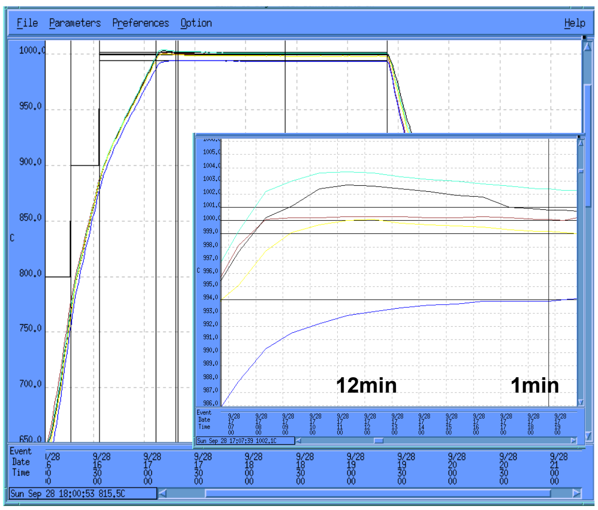

Figure 6. The maximized temperature ramp and stabilization time for the standard PID controller.

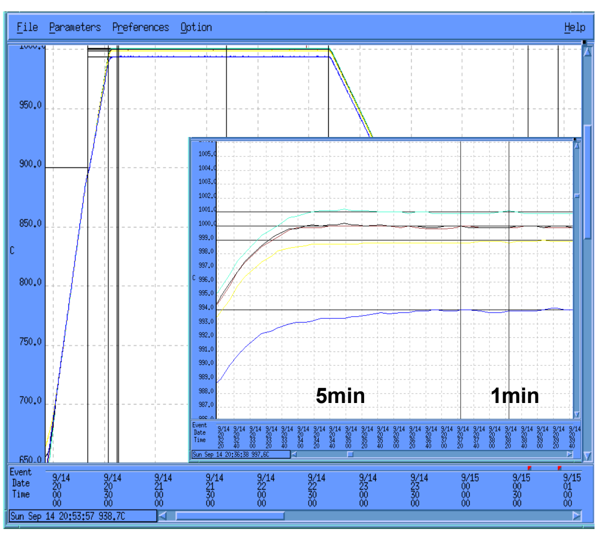

Figure 7. The maximized temperature ramp and stabilization time for the MBTC controller. The superb control of the MBTC allows for a faster ramp with less stabilization time.

Process Requirements	Standard PID	MBTC
650°C Stabilization	15 min.	5 min.
650°C–900°C Ramp	32 min.	25 min.
900°C-1000°C Ramp	33 min.	12 min.
1000°C Stabilization	12 min.	5 min.
Total Time to Process	**92 min.**	**47 min.**

Table 2. Required time to reach the process conditions for the standard PID and MBTC controllers.

4 CONCLUSION

The Semy MBTC system clearly demonstrates an improvement in temperature response by virtually eliminating end-of-ramp temperature overshoots and improving steady-state temperature control. Through the improved temperature response, the MBTC controller also improves measured process uniformity with increases in Cp and Cpk as much as 300% and 240% respectfully. Although the increase in uniformity varies per process, the improved temperature control eliminates temperature as a process variation.

The direct profile control of the MBTC eliminates the need for the profiling of a furnace. This fact, coupled with the decrease in cycle time from the reduction in temperature ramp and stabilization times, increases the wafer throughput of a vertical furnace by as much as 20% in this application.

The design of the MBTC allows for an easy incorporation into a vertical furnace without major constraints on the manufacturing environment. Thus, the MBTC minimizes the invested equipment installation time while providing temperature control improvements, leading to a significant improvement in furnace capability.

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