Programmable PID Temperature Control of Multi-Tube Multi-Zone Diffusion Furnaces

M.G. Guvench, R. Stone, S. Pennell and R.Worcester
University of Southern Maine

Abstract

This paper describes the design, operation and performance results obtained with a programmable temperature and gas flow controller designed to control a multi-tube multi-zone diffusion system. The system was built and used for 4" silicon wafer processing at University of Southern Maine's MicroFabrication laboratory. The diffusion furnace employed is a four-tube stacked Thermco furnace, with its each tube operating in three temperature zones powered from a bank of 3-phase transformers. The power delivered to each zone is controlled separately by varying the duty cycle of 40VRMS transformer outputs via zero-angle firing thyristors. The control system was built with off-the-shelf DAQ, digital and analog IO cards housed in a 586-class PC. Simultaneous PID control of twelve temperature zones and twelve switched gas lines was achieved with LabView operating under Windows'95. The controller is designed to operate as a slave to a programmable master scheduler which generates for each tube up to ten intervals of time in each of which temperature is varied linearly. In this way a piecewise linear variation of diffusion/oxidation temperature is obtained, allowing the wafer to go through a recipe of diffusion/oxidation/annealing sequence at various temperatures and in different gas compositions with fully controlled rates of ramp up or ramp down. A temperature control of ± 1 C RMS is shown to be achievable which is mostly limited by noise in the temperature readings.

1. Introduction

In the university operated microfabrication laboratories, unlike an industrial production setting, the diffusion/oxidation furnaces employed for semiconductor device and integrated circuit fabrication have very small average usage time due to the inherent low-volume of such operations[1,2]. In these laboratories the standard practice is to dedicate each tube of a diffusion/oxidation furnace to a different process, set the temperature of each tube at its dedicated process temperature and maintain the temperature at its constant value day and night. The wafer batch is loaded into the appropriate tube operating at the appropriate temperature with appropriate gas flows for a prescribed amount of time for each individual diffusion/oxidation cycle. Considering a four-tube set-up with each tube running at 10 KW, the amount of the electrical power wasted by such an operation is enormous.

The goal of this project was to control a diffusion system in a programmable way via a PC so that once the silicon wafers are loaded, a sequence of thermal processes could be commanded by the computer to the furnace tubes and the gas controllers to go through a recipe of temperature and gas compositions starting from and ending at a low stand-by temperature, thus achieving automation as well as conserving energy.

A complete silicon wafer process, depending on the complexity of the devices being fabricated, is made up of a number of thermal processing steps, namely oxidation, predeposition and drive-in diffusions and annealing. These are separated by groups of other processes involving photolithography, etching/deposition and cleaning. The thermal processes mentioned require temperatures typically in the range of 500 to 1100 C and a clean gas environment which is typically either one or a blend of three gases, nitrogen, oxygen and steam. For the control of defects and surface states or for other reasons, a simple process like wet oxidation in steam [3,4] may have to be preceded and proceeded with dry oxidation's and also other steps like cooling down at a controlled rate in an inert gas atmosphere. Such complex thermal processes can only be done an automated diffusion/oxidation system. Automated and computer sequenced processing in the same tube with minimum operator involvement is particularly suited in an instructional laboratory where students do the processing of their wafers. It minimizes manual loading unloading of wafers in between extremely hot furnace tubes which increases safety risks and results in exposure of the wafer to dust and contamination. A practical benefit is that the supervision time required is lessened. As a matter of fact with a networked computer doing the control and monitoring, the instructor and the students can monitor the process remotely without being forced to stay by the furnace. This becomes particularly important for some diffusion/oxidation steps which are too long to be completed within the few hours of scheduled laboratory time. An added benefit is that records of actual temperature vs time can be generated easily and kept in a data base for future reevaluations, comparisons, simulations or diagnostic purposes, again with a remote access option in a networked system.

Computer controlled diffusion/oxidation systems are standard equipment in industrial fabs and can be purchased from various vendors. However, the cost of such systems is prohibitively high on a scale of a typical university equipment budget. Recent availability of data acquisition hardware and software for PC's at affordable prices has created an opportunity to upgrade and automate older diffusion/oxidation equipment in university laboratories. The work reported here shows the feasibility of building such a PC controlled system with off-the-shelf hardware and software at a cost insignificant compared to the original equipment. The system built has been tested and in use for wafer processing in the MicroFabrication laboratory at the University of Southern Maine. In the following sections, the system built is described and performance results are presented.

2. Automated Diffusion/Oxidation System and Its Controller

This section describes the multi-tube multi-zone diffusion system and its programmable temperature and gas composition controller. A schematic representation of the system is given in Figure 1. It employs a four-tube stack Thermco furnace. This furnace can accommodate six-inch diameter quartz tubes to process wafers up to four-inches in diameter. Each tube is heated by three heater coils, constituting a three-zone system with three S-type thermocouples put through holes in the insulator at the center of each heating element for feedback. There is an extra thermocouple in the center zone for monitoring temperature independently, for overtemperature alarm circuits. Three gas lines, one N2 and two O2 are supplied to each tube. One of the O2 lines passes through a H2O bubbler for wet oxidation. The gas flows are controlled and monitored by a Tylan gas control box with each line passing through a mass flow controller and a solenoid valve. Figure 1 shows only one of the four tubes and their gas connections. The solenoids have buffer circuitry for easy interface to TTL compatible drivers. The heater elements are powered from a 3-phase 480VRMS line through four 3-phase step-down transformers delivering 40VRMS, one for each tube and with each phase powering a separate zone through independently firing thyristors. The thyristors are zero-angle fired to minimize the switching noise and control the amount of power delivered to the zones through the duty-cycle of the on/off cycles.

Control of 4 tubes with 3 zones and 3 gas lines each needs a minimum of 12 analog inputs, 12 analog outputs and 12 digital outputs. To meet this need a PC controller The programmable controller system designed employs a Pentium grade (Cyrix 586-120) PC running under Windows'95 and housing CIO-DAS 08/CM data acquisition and two CIO-DDA 06 analog output cards and an externally housed CIO-EXP 16 analog multiplexer card with a total of 16 S-type thermocouple inputs and 16 analog and 24 digital outputs [7]. The extra thermocouple inputs left from twelve zones were used for a redundant overtemperature security and shutdown procedure. The setup allows up to three gas lines per tube to be controlled via mass flow controllers. Originally a PID code written in-house in compiled Quick Basic was used to drive the hardware. This code which satisfactorily controlled the temperatures within +/- 4 degree Celsius over a temperature range of 600 to 1100 C was replaced with VI's "virtual instruments" written in LabView version 4.01 for enhanced flexibility, better noise filtering and superior graphical interface [5,6].

Design of the controller's software was done with the goal to isolate the user from the details of code yet to provide the user with a simple graphical interface but comprehensive enough to cover all possible scenarios of diffusion, oxidation and annealing processes. In order to achieve this the software routines were categorized as the "master" and the "slave". The "slave"s are the full controllers, each with the task of controlling the hardware to achieve a certain result. The "slave"s are responsible for monitoring individual zone temperatures and for bringing them up/down to the instantaneous value specified by the "master". The "master" on the other hand is responsible for supplying to each and every slave an input to follow in accordance with the starting time and the process recipe created by the user. PID control is embedded in the "slave" codes to achieve optimum responsivity. The furnace user interacts with the "master" only.

In its current form the controller for each tube can execute up to 10 sequential process steps of temperature "ramp up/down" and "hold steady" and their programmed gas compositions. This maximum number of processes was set at 10 for no reason other than the area it takes up on the vi window. The LabVIEW vi group named "MfabCtrl" which drives the hardware comprises of a collection of about 60 vi modules written to do the specific tasks involved. Each of these is constructed by combining the basic vi library elements supplied with the package [5]. Only three out of 60 vi's written are seen by and interact with the user.

When the program is started the window shown in Figure 2 appears on the screen, asking which tube to program. After the choice is made the window shown in Figure 3 appears displaying a recipe table, and the process starting time to be inputted and shows the real “current time” as reference. The process can be started in absentia up to 24 hours after the current time. The recipe table contains rows representing the process steps. For each step the final temperature and the duration time are specified. The master program interprets this as a linear variation of temperature within that interval of time beginning from a temperature written in the previous row and ending the temperature value specified in the current step. If the temperatures in two consecutive steps are chosen to be the same the temperature is held constant during that interval. Three gas buttons in the middle turn on the corresponding gas flow during that interval if their buttons are pushed in. After the recipe is filled the monitoring window shown in Figure 4 appears. This window displays simultaneously the status of all four tubes. Zone temperatures are displayed as numbers as well as in continuously updated line charts. The latter helps the user to see the trends. The three buttons show which gas lines are on at the current time. The program also records all of the zone temperature readings it received during the full length of the process and saves them in a file readable with a spreadsheet program for plotting and analysis.

3. Results and Discussion

Figures 5 and 6 show plots of the temperature readings recorded by the controller during a two-step diffusion process. The data was saved in a text file by the controller. Later, it was imported to QuattroPro and plotted. The plots display the unfiltered (unprocessed) temperature values based on the instantaneous capture of the thermocouple voltage. The reading/recording cycle was approximately 3-seconds; therefore the file contains about 2000 temperature points per zone. Zones are numbered as 1, 2 and 3 starting from the left (gas entrance side). Zone 2, therefore, represents the middle zone. This process recipe called for a 20 minute ramp from room temperature up to 800 C, hold it at 800 C , ramp it up to 1050 C in 15 minutes, hold it at 1050 C for 30 minutes and power down to zero for cooling back to the room temperature. All three zones were controlled with the same PID parameters, i.e., 7% proportional band, 0.8m reset and 1.6m rate. These number have been found to yield satisfactory results, but cannot be claimed to be the optimum. Observations made are: (1) Zone 2 which is the largest in terms of heat capacity cannot be raised from room temperature to 800 C in 20 minutes. Even at full power turned on it needs a minimum of 30 minutes for a 800 C rise; i.e., maximum slew rate of Zone 2 is 27 C/min. Corresponding numbers for the end zones are around 40 C/min. (2) Cool down rate is also the slowest for Zone 2 as expected. It is limited at 7 C/min, the end zones can cool at 12.5 C/min. (3) As long as the maximum slew rates are not violated the controller does its job with piecewise-linear temperature variation in accordance with the process recipe. Relative (percentage) overshoots in temperature are insignificantly small. (4) There is a visible increase in the noise level at 1050 C compared to at 800 C. The noise which is of high frequency compared to the rise and fall times of temperature is attributed to electromagnetic pickup from the thyristor-switched transformer currents.

In order to see the low frequency components of the noise generated at 1050 C the temperature data was low-pass filtered by group averaging. Figure 7 depicts plots of Zone 1, Zone 2 and Zone 3 temperatures all averaged in clusters of 20. This is effectively smoothing out the variations taking place faster than a periodicity of 60 seconds. Observed are, (1) Zones 1 and 3 do not display overshoots, Zone 2 displays a 5 C overshoot, (2) In all zone temperatures there is low frequency component of noise with a periodicity around 8-10 minutes. Fortunately, its amplitude seems to be less than 1 C RMS to be of any consequence for device fabrication.

4. Conclusions

The results presented clearly show that the diffusion controller system designed, implemented, tested in the lab and reported here performed according to expectations with temperature control as well as ± 1. It was shown that a controller for diffusion systems can be built with off-the-shelf inexpensive data acquisition hardware and software to upgrade and automate the diffusion systems in most university microfabrication laboratories.

Since its completion the system has proven itself to be an asset in our MicroFabrication laboratory. It has been reliably used in the fabrication of MOS and PN-junction diodes and in the development of a multi-project PMOS integrated circuit process for educational use at the University of Southern Maine[2].

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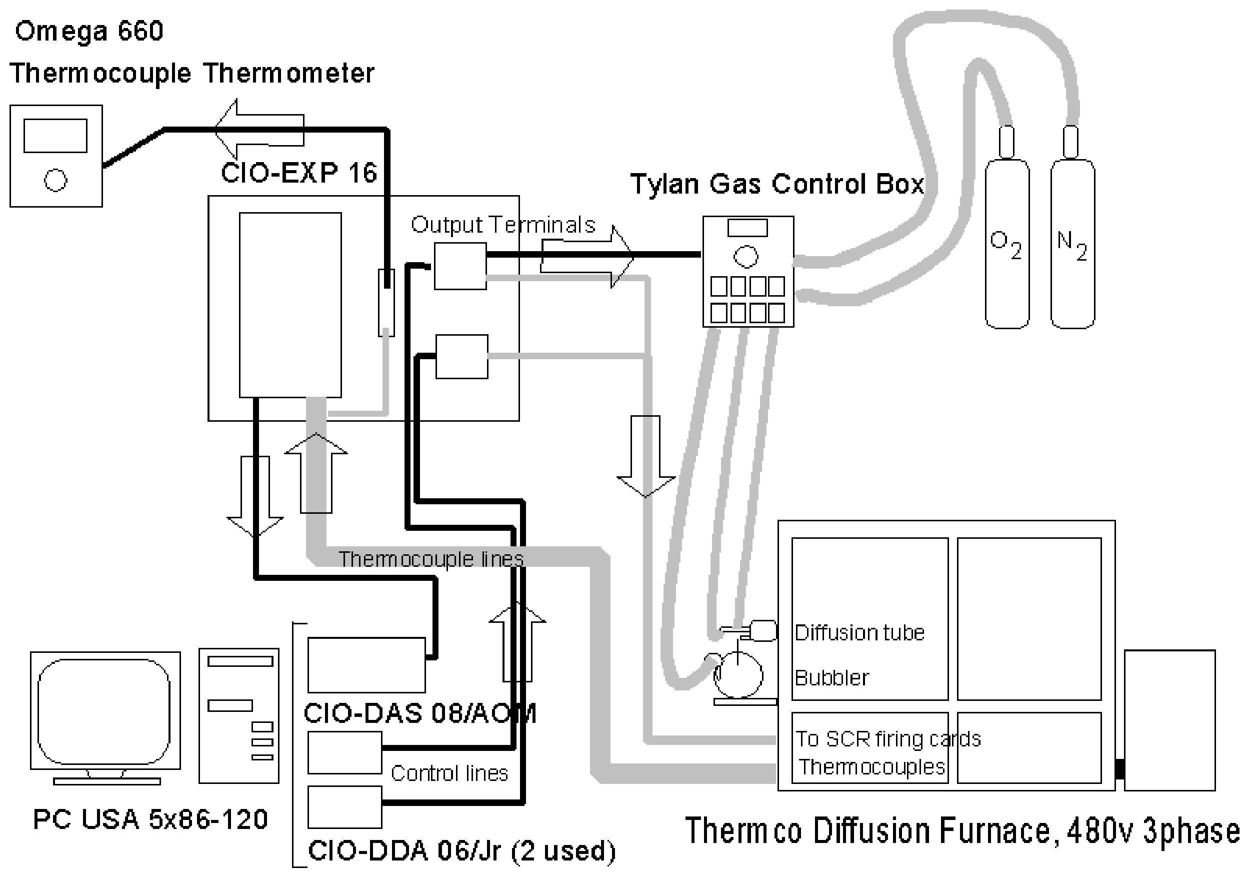

Figure 1. Schematic Diagram of The Diffusion System

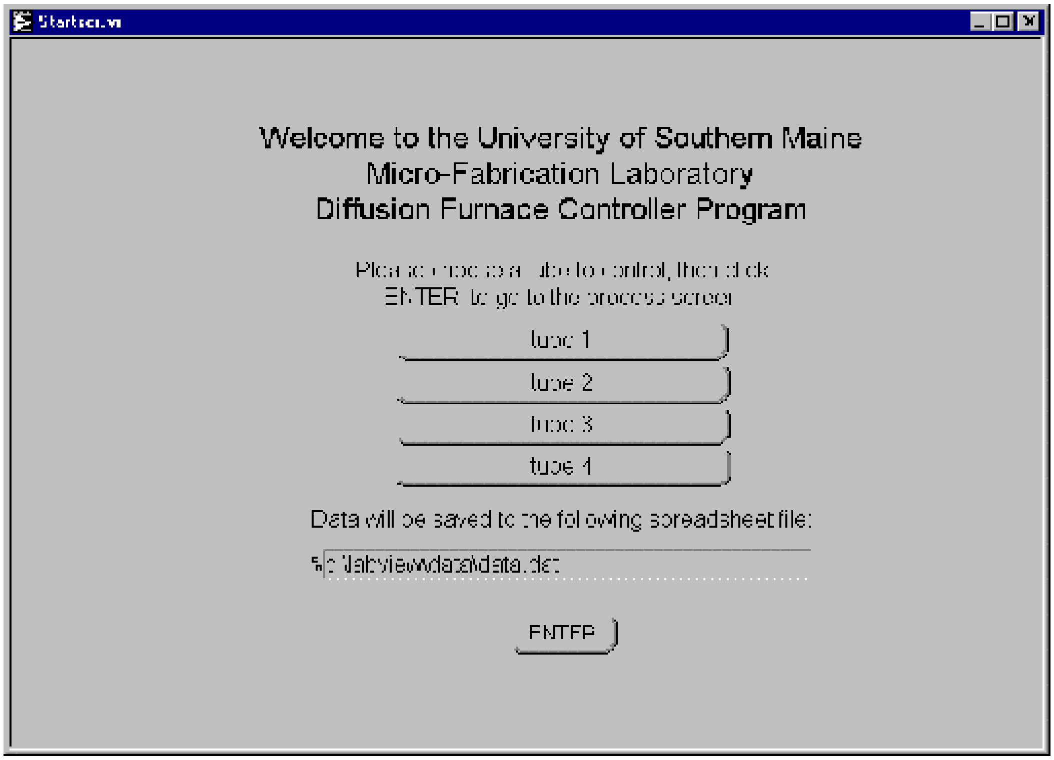

Figure 2. Controller Opening Window

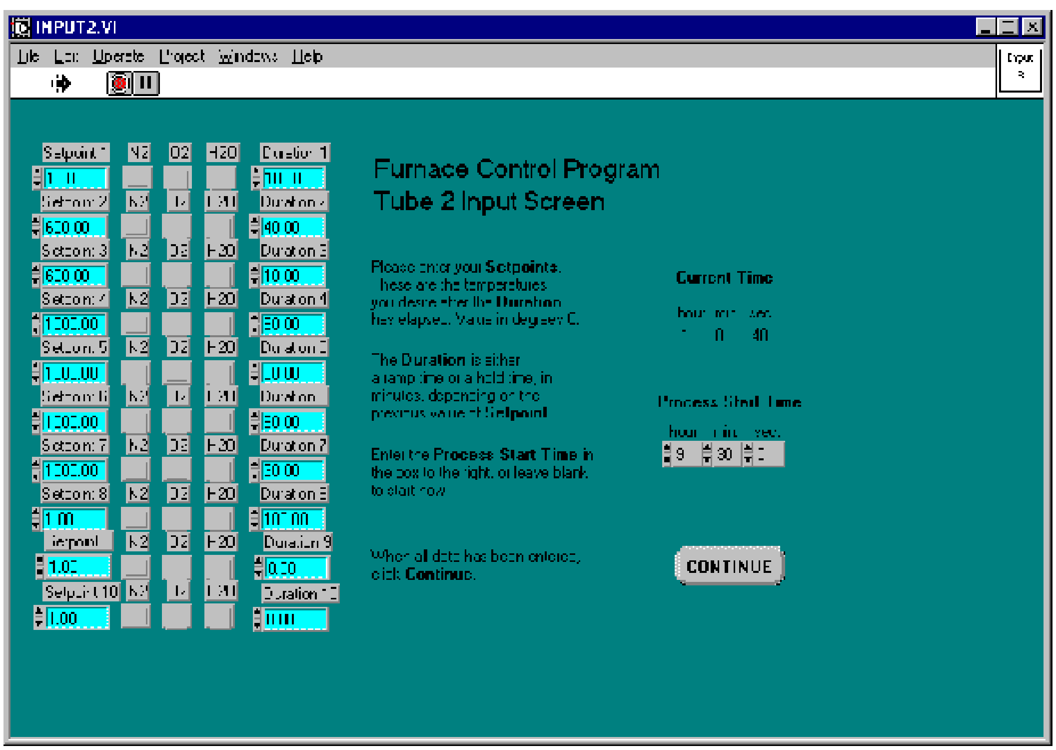

Figure 3. Process Master Controller Programming Window for Tube #2

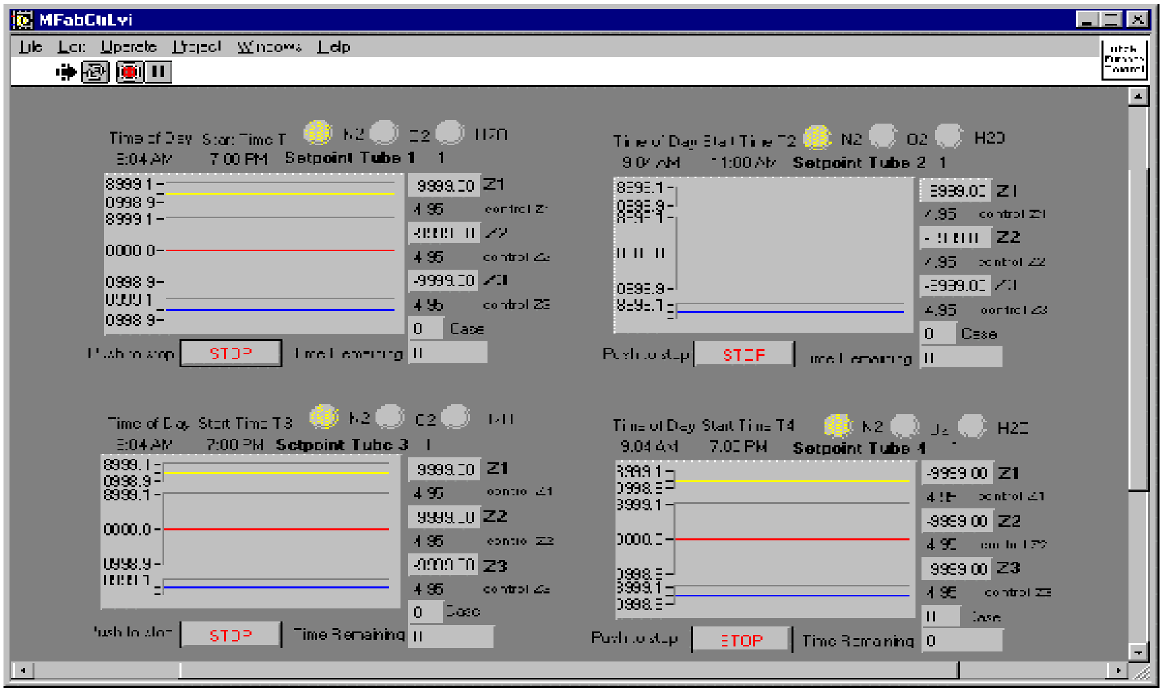

Figure 4. Temperature Monitor Display Window

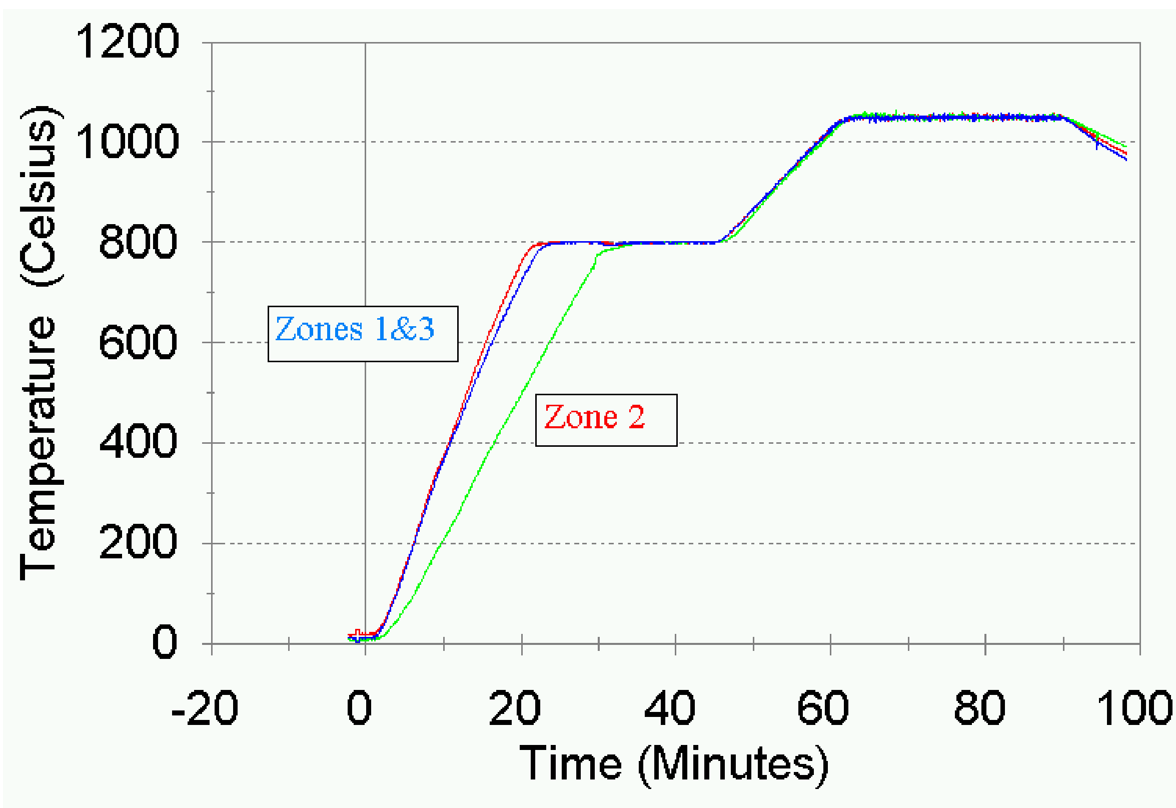

Figure 5. Temperature vs Time of Three Zones for a Two-Step Process

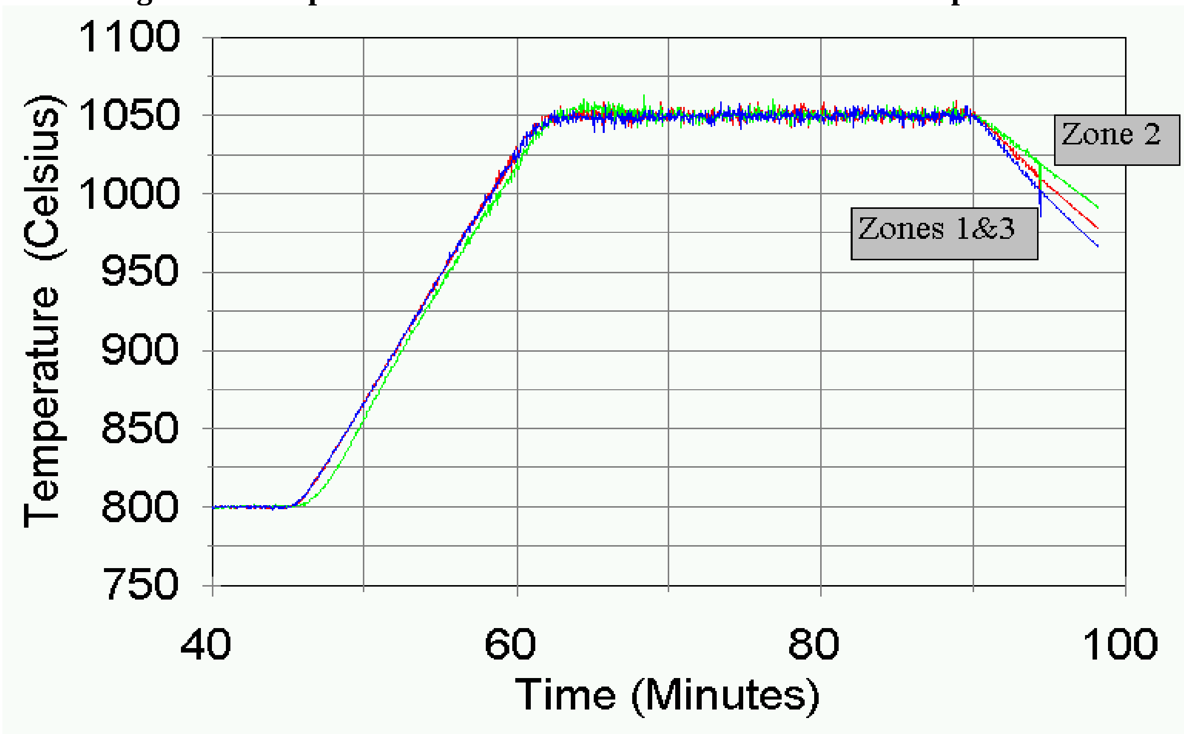

Figure 6. Unfiltered Temperature vs Time Data

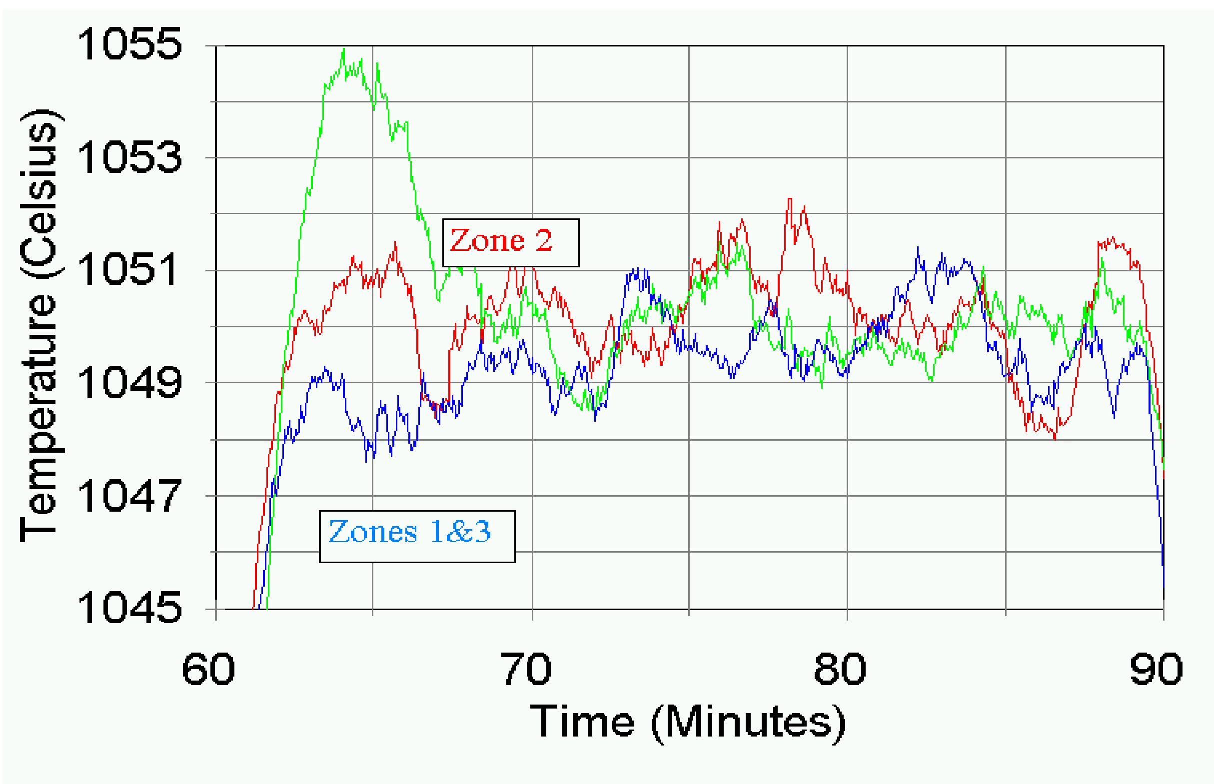

Figure 7. Filtered Temperature vs Time Data

This project has been funded by National Semiconductor and Fairchild Semiconductor Corporations.

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[6] LabVIEW is a product of National Instruments, Austin, Texas, www.natinst.com.
[7] CIO-xxx are products of Computer Boards, Inc., Middleboro, Mass., www.computerboards.com.

MUSTAFA G. GUVENCH

Mustafa G. Guvench received his B.S. and M.S. degrees in Electrical Engineering from M.E.T.U., Ankara in 1968 and 1970, respectively. He did further graduate work at Case Western Reserve University, Cleveland, Ohio between 1970 and 1975 and received M.S. and Ph.D. degrees in Electrical Engineering and Applied Physics. He is currently a full professor of Electrical Engineering at the University of Southern Maine. Prior to joining U.S.M. he served on the faculty of M.E.T.U., Ankara and Gaziantep campuses, Turkey and at the University of Pittsburgh. His research interests and publications span the field of microelectronics including I.C. design and semiconductor technology and its application in sensor development, finite element and analytical modeling of semiconductor devices and sensors, and electronic instrumentation and measurement.

ROBERT C. STONE

Robert C. Stone graduated from the University of Southern Maine with B.S. degree in Electrical Engineering in 1997. Prior to U.S.M. he attended Syracuse University specializing in bioengineering. His interests are software development, automated measurements and instrumentation. He is currently a graduate student at U.S.M.

RICHARD W. WORCESTER

Richard W. Worcester graduated from University of Southern Maine with B.S.degree in Electrical Engineering in 1996. He held various technical and engineering positions with Fairchild Semiconductor in South Portland, Maine. He was employed by Digital Equipment Corporation in Augusta, Maine as Senior Engineer until recently when he established his own private business.

STEVEN S. PENNELL

Steven S. Pennell graduated from the University of Southern Maine with B.S. degree in Electrical Engineering in 1997. He held technical positions at Konica and National Semiconductor in Portland, Maine. Currently he is employed at Allegro Microsystems, Worcester, Massacusetts as a Process Engineer specializing in chemical mechanical polishing and thin film deposition.