Technical Paper

Temperature Control of Semiconductor Processing Machine

Kazuhiro Mimura

Temperature control of the semiconductor process is the key factor for its quality and productivity. Recent trends such as the rapidly shrinking design rule promote an increase in the number of chemical and complex processes, which require higher temperature controllability. This paper introduces our recent advances in the PID control algorithm and tuning technique that were applied to a DI water heater and CS heater.

Key Words: *Temperature control, PID control, Feedforward control, Disturbance observer, Automatic tuning*

1. Introduction

Temperature control of the semi-conductor process is the key factor for its quality and productivity. The recent trend for further shrinking of design rules has accelerated changes in materials for transistor electrodes, oxide films and insulating films to break through the boundary for performance enhancement, a review of the electrode structure and other changes. As a result, the process has become complex through the use of many chemicals, changes in operating conditions and other

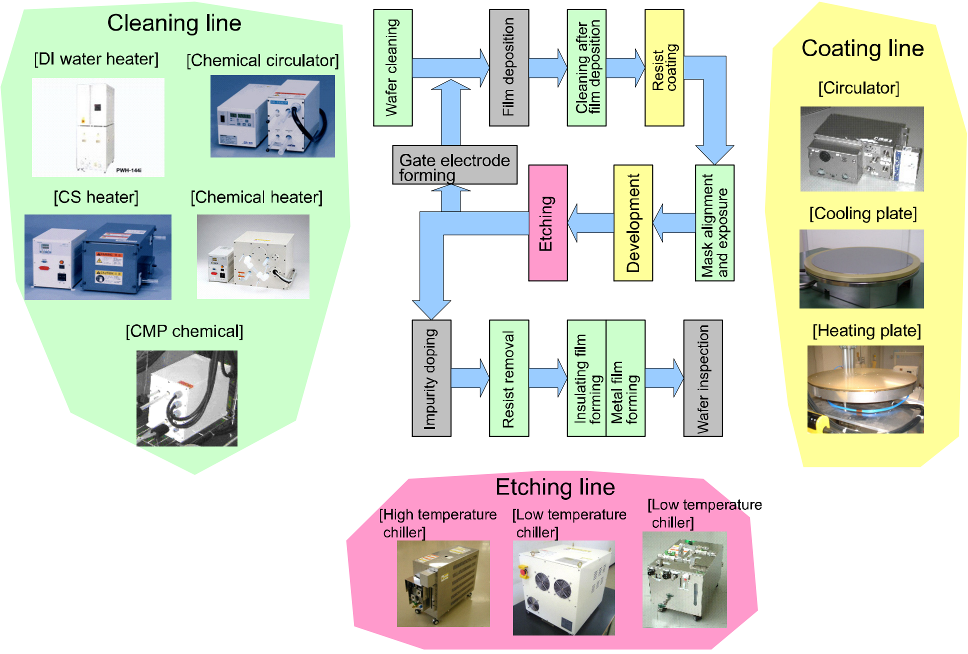


Fig. 1 Areas of wafer fabrication process in which our products are used. (Colors of processes show the colors of our product groups)

factors. The performance required on temperature control is therefore becoming more demanding. To meet this situation, we are making various efforts to improve the performance of temperature control. This paper discusses "Advanced PID control" for a DI water heater and "Advanced PID tuning" for a CS heater as an example of our activities. In "Advanced PID control" of a DI water heater, a robust system has been build against fluctuation of flow rate and/or lamp heater power by combining feedforward control and disturbance observer with PID control. In "Advanced PID turning" of a CS heater, PID parameters that are more optimal than by the conventional method can be obtained by adding another indicator to the ultimate gain and ultimate period.

2. Outline of Use of Our Products in Semiconductor Manufacturing Process

Our temperature controllers are used in the "wafer fabrication process" of the semi-conductor manufacturing process that builds in integrated circuits on the wafer. **Figure 1** shows our products related to each process in the "wafer fabrication process." They are roughly classified into the "cleaning line" for wafer cleaning, "coating line" for temperature control of a resist and wafer itself and "etching line" mainly for temperature control of the process chambers. The proportion of "cleaning line" products in particular is high and these products are our mainstay products.

Our products are classified into three groups from the standpoint of control as shown in **Fig. 2**. In the diagram, transfer function "A(s)" is a heat exchanger for heating and cooling, "B(s)," a tank or a chemical bath, "C(s)," a controller and "S(s)", a temperature sensor. In the fluid heating product line of Classification I, a fluid that is fed to a heat exchanger is directly supplied to a user system. This product line therefore does not have a tank or a liquid bath. The heat exchanger, controller and sensor are all our products and these products form a closed loop control system itself. One characteristic of this product line is that, therefore, controller tuning can be conducted during the development stage. The DI water heater, plates that do not use a fluid and the like belong to this classification. A fluid circulates in Classification II and a tank is installed. A fluid that is heated or cooled by a heat exchanger returns to this tank through user equipment. This classification includes a tank, heat exchanger, controller and sensor all of which are our products. In this classification, controller tuning during the development stage is easy as in Classification I. The chiller and circulator in the etching line are in this classification. In Classification III, as in Classification II, a fluid heated or cooled in a heat exchanger circulates through a liquid bath of the user. Unlike Classification II, a liquid bath and sensors are located on the user system side and controller tuning cannot be performed during the development stage, requiring controller tuning at the site. In all these classifications, control performances are required such as (1) Fast rise characteristic, (2) Small overshoot, (3) Fast recovery

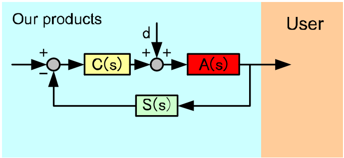
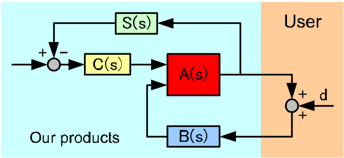
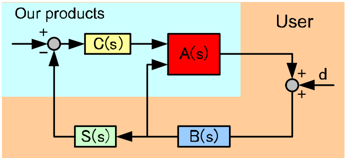
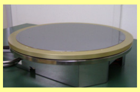
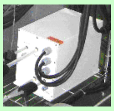
Classification	I	II	III
System configuration			
Characteristic	· Controller, heat exchanger and sensor are inside the system. · A fluid does not circulate in fluid heating. (One-path) · Tuning is relatively easy.	· Controller, heat exchanger, tank and sensor are inside the system. (Circulator does not have tank) · A fluid circulates. · Tuning is relatively easy.	· Controller and heat exchanger are inside the system. Specifications of tank, liquid bath and sensor differ from one user to another. · A fluid circulates. · Tuning is absolutely necessary.
Our products	[DI water heater]  [Cooling plate]  [Heating plate] 	[High temperature chiller]  [Low temperature chiller]  [Low temperature chiller]  [Circulator] 	[Chemical circulator]  [CS heater]  [Chemical heater]  [CMP chemical] 

Fig. 2 Classification of our products from standpoint of control

during disturbance, (4) Temperature accuracy from 1.0°C to 0.1°C and (5) Uniformity of inplane temperature and transient temperature profile with the plates.

3. Advanced PID Control – Example of DI Water Heater

PID control belongs to the category of classical control theory and its history dates back more than 80 years. PID control still accounts for more than 90% of control in the whole industry for the following and other reasons. (1) Simple structure, (2) Easy to understand for the user and (3) Excellent control performance even though the structure is simple. Temperature control of semi-conductor processing machines is also predominated by PID control for the foregoing reasons. However, in some cases, PID control alone is not adequate to meet specification requirements that are becoming stricter such as control performance and cost. These cases seem to be easily solvable using a advanced control technique such as modern control theory and robust control. However, in general, advanced control techniques are more difficult than with PID control in terms of easiness of selection of optimum values for feedback gains and controller tuning at site, as well as handling actuator saturation. PID-based "advanced control" which merges other control theories and enhances control performance while retaining the foregoing advantages of PID control, is, therefore, considered as an alternative. We employ both feedforward control and a disturbance observer for PID control regarding temperature control of the DI water heater. This system is a temperature control system that is robust against disturbances such as flow rate fluctuations, lamp output dispersions and lamp wire breakage through the following features. (1) Quick compensating operation against flow rate fluctuations utilizing advantages of feedforward, (2) A high degree of freedom of control without adding a temperature sensor, that is, without increasing cost, compared with conventional systems by employing a disturbance observer and (3) Solution of the saturation problem peculiar to systems with a serial structure by applying a control structure of the disturbance observer.

3.1 Outline of DI water heater

The DI water heater supplies hot DI water to the wafer cleaning system for cleaning and dilution of chemicals. **Figure 3** shows a photo of the heating bottle in the DI water heater and system configuration of the heater. The bottom of the figure shows the cross section of the heating bottle that is made of quartz. Six hollow holes are provided in the bottle and a halogen lamp is supported in each of the holes. DI water passing through the bottle is heated by radiation heat of the halogen lamp. The bottle generates 24kW of power and five models are available in accordance with the heating capacity, 24, 48, 72, 96 and 144kW. When more than one bottle is installed, flow paths of the bottles are connected in series as illustrated in Fig. 3 to gradually heat DI water. Temperature of the bottles is controlled roughly by the following two methods. The first method controls the temperature of the top bottle (mostly downstream) only by PID control and the other is to supply the electric power to the bottles at a fixed rate. The number of temperature sensors required can be reduced with this method, but the degree of freedom of control is low. The second method installs a temperature sensor at the outlet of each bottle, which is controlled by PID control. Each bottle is independent in this method and can be controlled independently so that degree of freedom of control is high. However, the same number of temperature sensors as that of bottles is needed, thus increasing the cost including cost of peripheral devices. Our previous "N series" products employed the former method. The new "i series" products use a disturbance observer, which estimates outlet temperatures of the remaining bottles based on the sensor temperature of the top bottle so that each bottle can be controlled by PID control without increasing the number of sensors, that is, without increasing the cost.

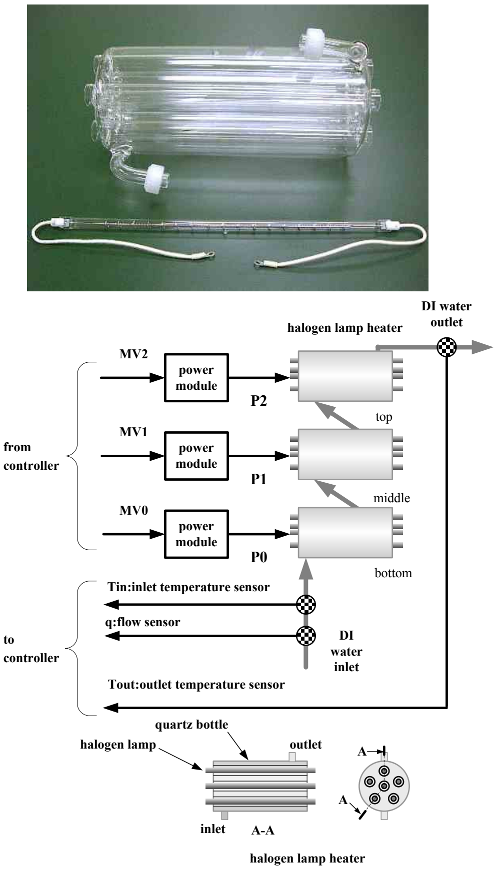


Fig. 3 Photo of heating bottle in DI water heater and system configuration

3.2 Change in cleaning system

As illustrated in **Fig. 4**, the wafer cleaning method is divided roughly into three types. The batch multi-bath method is the oldest method among these three methods and sequentially dips wafers in baths that contain different chemical solutions. In this method, DI water is flowed at a constant flow rate and this method was the main method. However, as cleanliness of wafers has become high, a one-bath method has been introduced to clean wafers by changing chemical solutions in one bath while keeping wafers dipped in this bath. Since wafers are not exposed to outer air with this method, risks of wafer contamination can be lessened. This method allows changing the feed flow rate of DI water depending on the process. The process has become more complex and optimum conditions have been required for each cleaning process. A single wafer cleaning method is used to clean wafers one by one. This method also allows changing the feed flow rate of hot DI water as in the one-bath method. At present, these three methods are used suiting purposes and cost level.

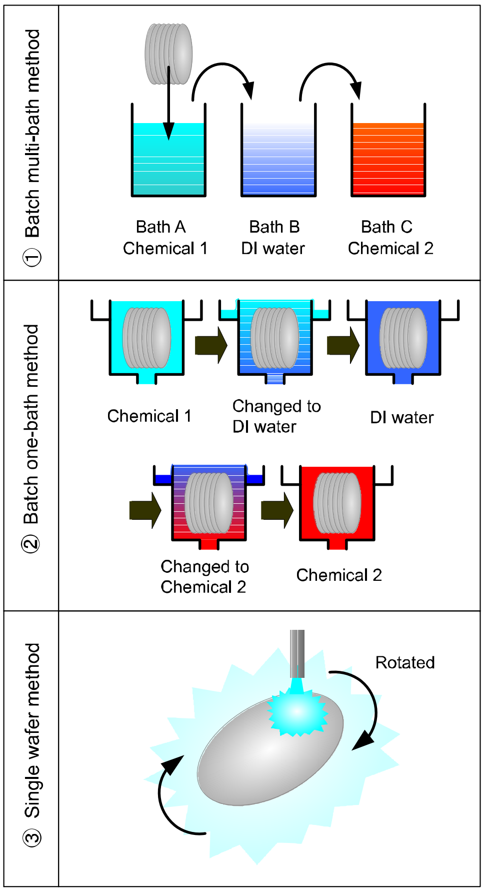


Fig. 4 Wafer cleaning methods

3.3 Combined use of feedforward control

As mentioned above, in many cases, hot DI water heated in the DI water heater has been flowed in the batch multi-bath process at a constant flow rate. However, the method to change the flow rate of hot DI water fed to the process has become the mainstream method as the number of batch processing baths is reduced to one and through the introduction of the single wafer process. For this reason, a change in the flow rate becomes a disturbance for some DI water heaters, presenting fluctuations of the bottle outlet temperature as a problem. This is caused by an inability of the controller of the conventional systems to compensate operation before the temperature sensor detects flow rate fluctuations as temperature fluctuations. The new system combines feedforward control to PID control. The configuration of this new system is illustrated in **Fig. 5**. To simplify the configuration diagram, a temperature sensor is provided to each of all the bottles. In feedforward control, flow rate fluctuations are detected by a flow rate sensor and electric power needed for flow rate fluctuations is calculated to be added to the PID controller output. Compensation operation of the controller is therefore activated immediately after a flow rate fluctuation occurs.

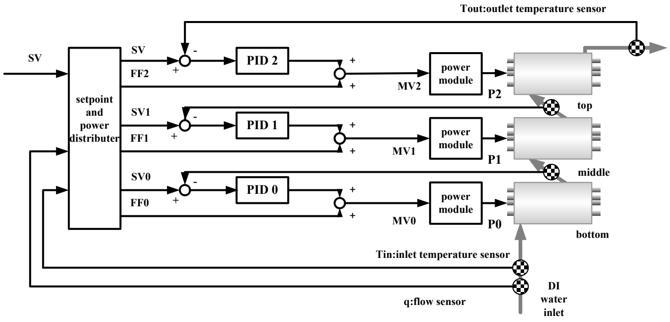


Fig. 5 PID control + Feedforward control

Figure 6 compares effects of combining feedforward control with those of the conventional system. The deviations in the bottle outlet temperature are observed when the flow rate is changed in a step shape (30L/min ±10%, 27L/min ↔ 33L/min). A temperature fluctuation width in a flow rate increase or decrease exceeding 2°C with PID only can be reduced to about 0.2°C, or 1/10.

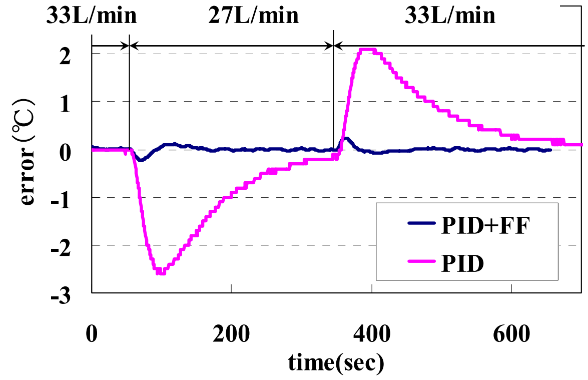


Fig. 6 Flow rate fluctuation test

3.4 Combined use of disturbance observer

One of the heating bottles of the DI water heater can be considered as a subsystem in the mode of Classification I illustrated in **Fig. 2** consisting of a controller, heat exchanger and sensor. When more than one bottle is installed for a system 48kW or larger, the same number of these subsystems as that of bottles are serially connected. This structure is generically shown in **Fig. 7**. In the diagram, Gi($_s$) is a plant that contains a heat exchanger and a sensor and Ci($_s$) is a controller, while the subscript "i" shows the number of subsystems. If a target value cannot be achieved by one subsystem of this structure, the output can gradually approach the target value by serially connecting subsystems. However, errors in the upstream process propagate to the downstream process. Depending on the magnitude of errors, the downstream process will no longer be able to compensate an accumulation of these errors and will saturate, thereby failing to reach the final target value and offset remains as a problem. To solve this problem, command values to all bottles must be distributed appropriately and controlled without causing saturation in the middle. This control system combines a disturbance observer to PID control and is not intended to cancel a disturbance by estimating it as conventional usage. This system accomplishes control without causing any saturation to the subsystem in the middle by appropriately distributing command values to the bottles even in those systems that have modeling errors by applying the control structure of type 1 belonging to a disturbance observer.

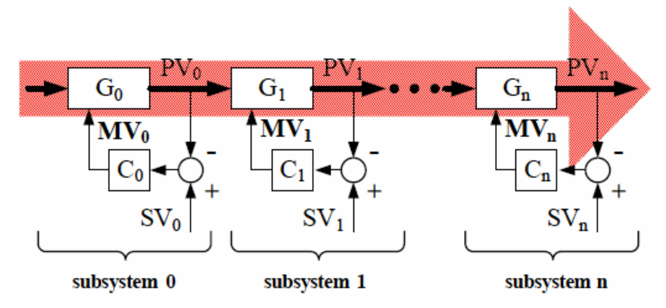


Fig. 7 Serially connected structure of subsystems

Along with the state feedback, the observer is a technique that is the core of the modern control theory and estimates the quantity of a state, which cannot be observed directly by a sensor, using a plant model. The disturbance observer collectively assumes the state quantity of a plant, disturbance that is actually applied, modeling errors and other elements and estimates them as in other state quantities. A disturbance can be cancelled by applying an estimated disturbance to the input side. The disturbance observer is widely used especially in the field of motion control and is cited frequently in academic literature also.$^{1), 2)}$ Assuming that a step-like disturbance w is added to the input of a plant of p inputs and one output, the plant model can be expressed as a state space form.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Bw(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

where A is an $n \times n$ matrix, B, an $n \times p$ matrix, C, a $1 \times n$ matrix, $x \in R^n$, a state space vector, $u \in R^p$, an input signal, y, output and $w \in R$, a disturbance. The augmented system that includes disturbance w as a state can be expressed as follows:

$$\begin{aligned} \begin{bmatrix} \dot{x}(t) \\ \dot{w}(t) \end{bmatrix} &= \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) \\ &= Aa \cdot \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} + Ba \cdot u(t) \\ y(t) &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} = Ca \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} \end{aligned} \tag{2}$$

If (Aa, Ca) is observable, we can construct a disturbance observer as (3).

$$\begin{bmatrix}\dot{x}(t)\\ \dot{\hat{w}}(t)\end{bmatrix} = Aa\begin{bmatrix}\hat{x}(t)\\ \hat{w}(t)\end{bmatrix} + Ba\cdot u(t) \qquad (3)$$
$$+ L(Ca\cdot x(t) - Ca\cdot \hat{x}(t))$$

where $\hat{x}$ and $\hat{w}$ are estimated states and L, an observer gain. **Figure 8** shows a 72kW system that includes a disturbance observer. To simplify the figure, the feedforward blocks are omitted. The plant model that includes a disturbance uses a fifth order model. The estimated outlet temperatures of the bottom and middle bottles are compared with set-point of these bottles that are distributed appropriately by a set-point distributor and are input to each PID controller as deviations.

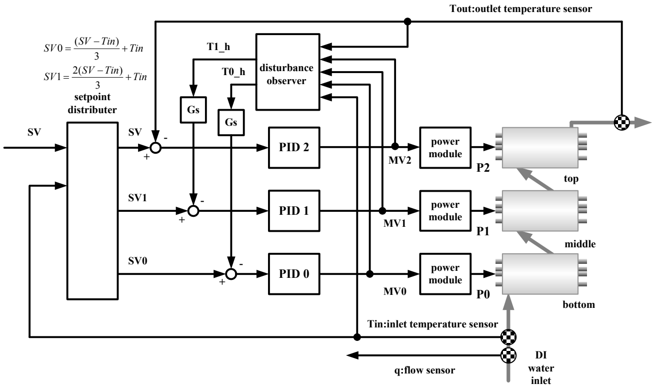


Fig. 8 PID control + Disturbance observer

The employment of a disturbance observer not only reduces the number of sensors, but also controls with optimum output without leaving offset even if lamp output disperses and lamp wire breaks in a system that has a serial structure. The internal structure of the disturbance observer for 72kW shown in Fig. 8 is illustrated in **Fig. 9**. Assuming that an equal disturbance is added to all inputs, the number of integrator becomes only one. As a result all command values are able to be distributed appropriately.

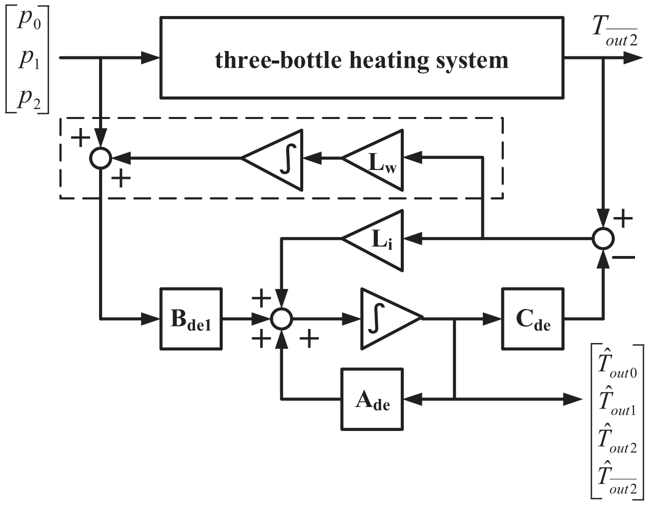


Fig. 9 Internal structure of disturbance observer

The effect of the disturbance observer is shown in Fig. 10. Fearing a possibility of lamp wire breakage, lamps of all the middle bottles are turned off in 100 seconds after the bottle outlet temperature becomes steady state at the set-point. In **Fig. 10(a)**, a disturbance observer is used. In **Fig. 10(b)**, PID control is used by installing a temperature sensor in each of all the bottles. When a disturbance observer is used, the bottle outlet temperature recovers to the original set-point temperature in about 100 seconds after the lamps go off, at which time the command value of each bottle is controlled to an almost equal value. Compared with this, recovering to the set temperature is not accomplished in PID control only. This is because further compensating operation is not accomplished even if the middle bottle has not reached a set-point as the outlet temperature of the bottom bottle has reached the set-point.

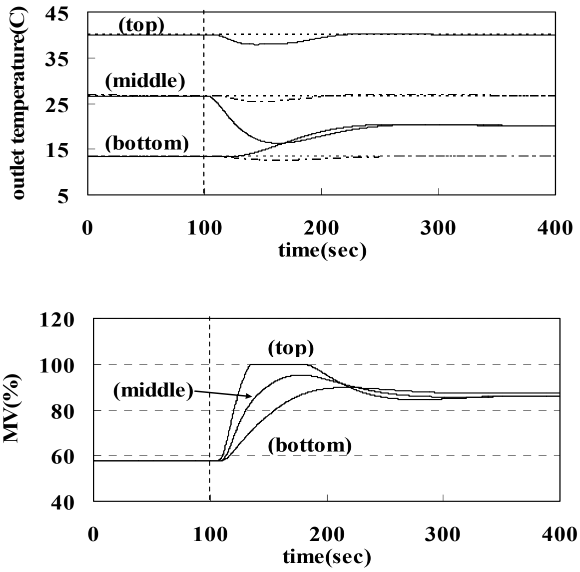


Fig. 10 (a)

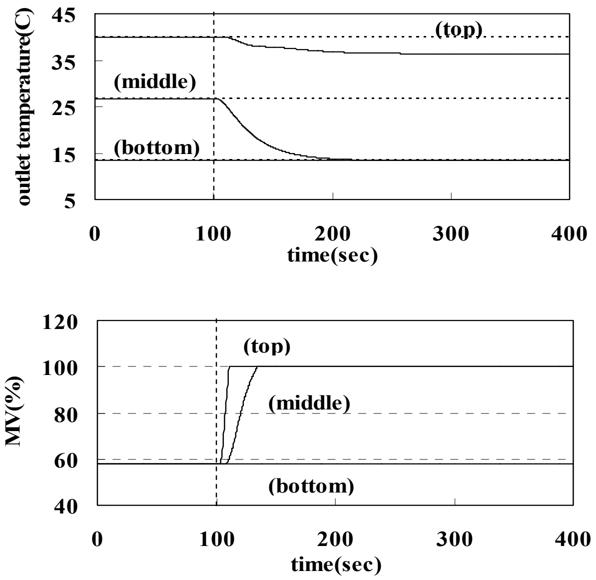


Fig. 10 (b)

Fig. 10 Results of temperature control assuming lamp wire breakage

(a) Disturbance observer is also used
(b) PID control installing a sensor to each of all bottles
Top graph: Bottle outlet temperature, Bottom graph: Command value

4. Advanced PID Tuning - Example of CS Heater

Selection of PID parameters is mandatory in PID. Entire systems belonging to Classifications I and II by the control mode mentioned above are located inside equipment and parameters can be decided during the development stage. Compared with this, however, the system that belongs to the Classification III has a chemical bath and sensor that greatly affect system dynamic and are located on the user side so that their specifications vary from one user to another. PID tuning is necessary during a change in a process or operating conditions as well as at new system rise of the equipment. Optimum tuning depends much on the experience of skilled operators and the length of time spent in this work is unnegligibly long. This has been a problem since the birth of PID control. However, in 1942, Ziegler and Nichols proposed tuning rules as tuning guidelines obtained from a very large volume of experiment data.3) Values that are "not exactly right, but you are close to getting it" can now be obtained. However, even if this tuning rule is used, some preparation such as conducting an open loop step response test (step response method) or forcing the system to its stability limit to calculate ultimate gain and ultimate period (ultimate sensitivity method) were needed. Automatic tuning automates this time-consuming tuning. The limit cycle method4) proposed by Åström in 1984 can very simply realize a ultimate sensitivity method and is used in almost all general-purpose temperature controllers at present. However, as the ultimate sensitivity method is the basis, obtained PID parameters are not necessarily optimum values. This is because ultimate gain and ultimate period obtained from the ultimate sensitivity method are "point" information in dynamic characteristics of a system. As there are many equations of straight lines that pass one point, it is difficult to perfectly identify dynamic characteristics of a system only by ultimate gain and ultimate period. A variety of research is conducted even at present to solve this problem. 5), 6)

We have devised a method to extract characteristic points of a temperature waveform during implementation of the limit cycle method and to incorporate them in the tuning rule as another piece of information in addition to ultimate gain and ultimate period. The application of this tuning rule to our product, the CS heater, has enabled us to reduce overshoot during a heat up and a disturbance recovery compare with the conventional tuning rule.

4.1 Overview of CS heater

The configuration of the heating system by a CS heater is shown in **Fig. 11**. The CS heater is mainly used in temperature control of a chemical for wafer cleaning. Heating is performed by radiation heat of a halogen lamp heater, as in the DI water heater, and the chemical between the chemical bath and heater is gradually heated by circulating it between them by a pump. All the characteristics such as the capacity of a chemical bath, heat radiation materials, circulation flow rate, physical property of chemical and sensor characteristics differ from one user to another and PID tuning is needed to obtain optimum PID parameters.

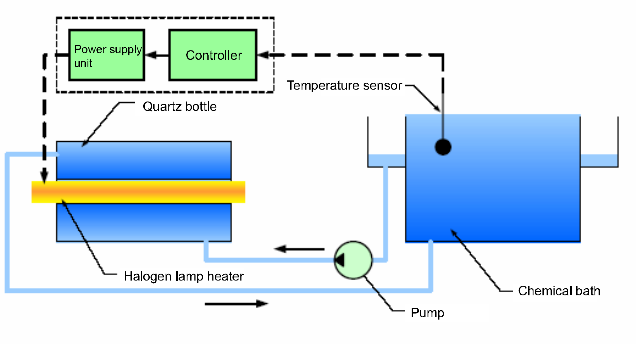


Fig. 11 Configuration of CS heater

4.2 Optimization of tuning

Figure 12 shows a temperature waveform during tuning by the limit cycle method. The CS heater only radiates heat spontaneously during its cooling and its temperature waveform becomes vertically asymmetric as shown in the graph. Given this phenomenon, the ratio between the heating time and cooling time is considered as one of the indicators that represent the characteristics of its process and "*X*" is created.

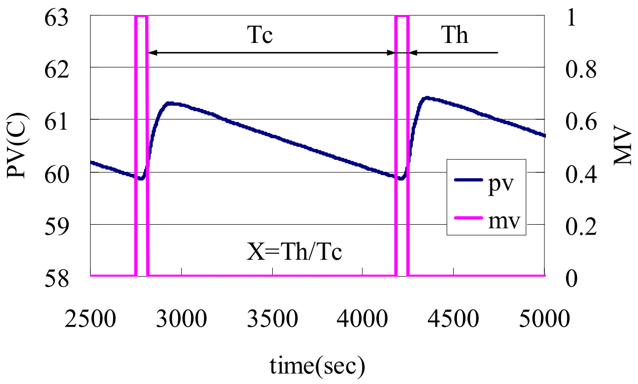


Fig. 12 Waveform in limit cycle method

The procedure shown in **Fig. 13** was used to examine the relationships among the process ultimate gain and ultimate period, as well as an optimum PID parameter in relation to *X*. First, operating conditions anticipated for the CS heater were considered and levels were created by setting and combining ranges for the conditions. The principal conditions included the bath volume, set temperature, circulation flow rate and sensor time constant. With respect to these levels, a plant is expressed by "Third order plus time delay system" and a ultimate gain *Kc*, ultimate period *Tc*, *X* and other elements are calculated by the limit cycle method. Next, a level for PID parameters is created based on the ultimate gain and ultimate period. Response waveforms during a temperature rise and application of a disturbance are calculated in simulation. An overshoot *OS*, settling time *TS*, evaluation indicator and other elements are then calculated. The "evaluation indicator" mentioned above is based on the integral value of a deviation *e(t)* and can be expressed as follows.

$$ITAE = \int_0^\infty t\left|e(t)\right|dt$$
$$IAE = \int_0^\infty \left|e(t)\right|dt \qquad (4)$$

"ITAE" is frequently used as a rise characteristic and "IAE," as a characteristic when a disturbance is applied. In addition to these indicators, a sensitivity *Ms* was calculated based on the controller and plant model. The sensitivity is the maximum value of a sensitivity function and can be expressed as follows assuming that a transfer function of the plant is $G_p(s)$ and that of the controller, is $G_c(s)$.

$$Ms = \max_{0 \le \omega \le \infty} \left| \frac{1}{1 + G_p(i\omega)G_c(i\omega)} \right| \qquad (5)$$

Generally, *Ms* = 1.3 to 2 is suitable. [7)]

Values thus obtained in simulation are evaluated by the following evaluation functions and a combination of their minimum values is used as the optimum value of a PID parameter.

$$J_{set} = \sqrt{w_1 OS^2 + w_2 ITAE^2}$$
$$J_{dis} = \sqrt{w_3 IAE^2 + w_4 Ms^2} \qquad (6)$$

where $w_i i$ = 1,2,3 and 4 are weights. Lastly, the optimum value of each level is converted into magnification ratios of *Tc* and *Kc* and is expressed as a function of *X*. Assuming the magnification ratios to be Y_1 and Y_2, respectively, the following can be obtained.

$$Y_1 = f(X), \quad Y_2 = g(X) \qquad (7)$$

Calculating *Tc*, *Kc* and *X* by the limit cycle method using these values, optimum PID parameters can be calculated as follows:

$$Kp_{set} = Y_1 Kc = Kc \cdot f(X)$$
$$Ki_{set} = Y_2 Tc = Tc \cdot g(X) \qquad (8)$$

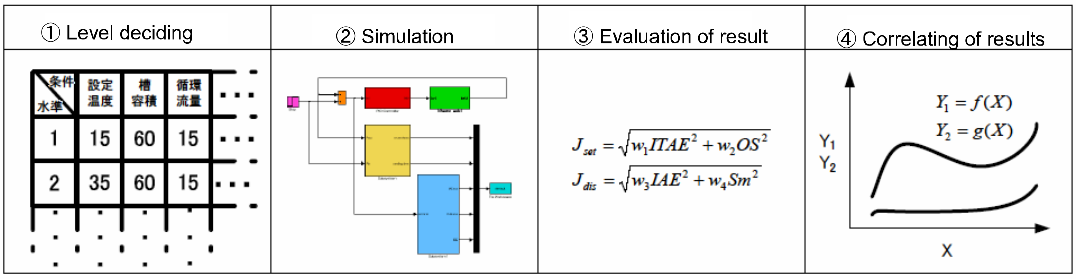
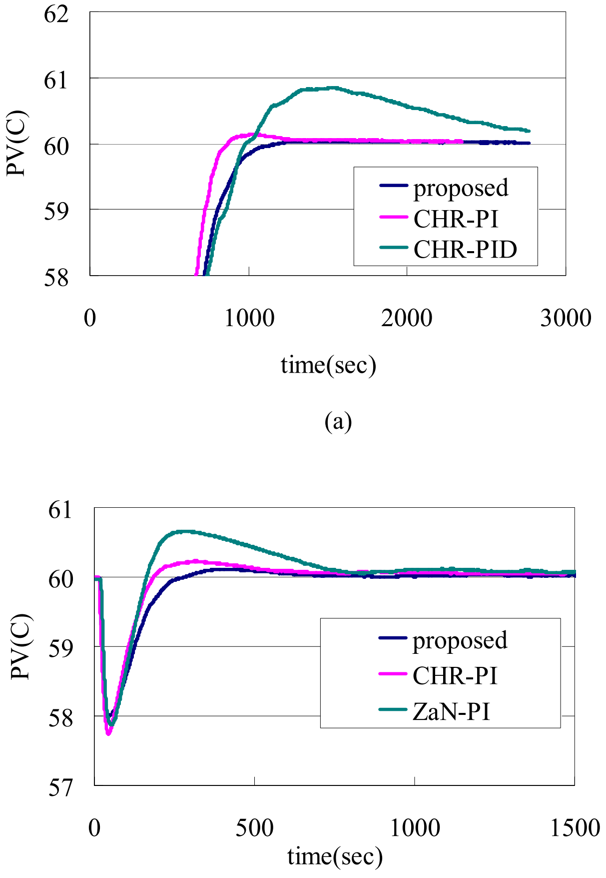


Fig. 13 Procedure for correlating characteristic quantity X and PID parameters

Figure 14 shows the results of the experiment in comparison with the conventional tuning rule. In the graph, “ZaN” indicates the Ziegler and Nichols method, while “CHR” indicates the Chien, Hrones and Reswik method. Characteristics during a temperature rise are shown in **Fig. 14(a)**. **Figure 14(b)** shows characteristics during a temperature recovery when a dummy, which is equivalent to fifty 300mm wafers, is put into the bath as a disturbance. The graphs show that the proposed method reaches a set-point producing a less overshoot than conventional method in both cases.



(a)

(b)

Fig. 14 Comparison of tuning rules
(a) Rise characteristic and (b) Disturbance recovery characteristic

5. Conclusion

Our activities in the temperature control technology of semi-conductor processing machines are explained from the standpoints of “Advanced PID control” and “advanced PID tuning method” using a DI water heater and CS heater as examples. In the future, a “high flow rate,” “low flow rate,” “environmental friendliness” and “energy conservation” will become important keywords in addition to the control performance explained in this paper.

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Introduction of the writer

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Currently assigned to KELK Ltd., the System R & D Dept.

[A few words from the writer]

Seven years have passed since I was assigned to the control of temperature control equipment of semi-conductor processing machines. PID control requires in-depth knowledge and is a very challenging research theme. We will continue research to achieve control that is higher in function and is easier to use for users.