PID Temperature Control Improvement of Semiconductor Furnace Using Fuzzy Inference

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In the semiconductor field, it becomes difficult to satisfy recent demands on the temperature control performance using the standard PID controller. Still more, to optimize the PID controller, much time is usually required for trial-and-error tuning. But simple and intuitive property of the PID controller is useful in production fields. We have developed a new method that improves PID controller performance, setting PID parameters for steady-state characteristic at first, and later compensating for transient characteristics. This paper describes an attempt to expand the applicable range of the PID controller using fuzzy inference, and to reduce the effort for PID parameter tuning.

***Key Words**: fuzzy inference, furnace, PID, temperature control, semiconductor*

1. Introduction

Recently, one generation of the semiconductor shifts to the next every three years in terms of higher integration and minuteness. Design rules or the thickness of gate oxide film are also changed about 0.7 times smaller during the shift from one generation to the next. At the same time, wafers are required to have larger diameters for reducing the manufacturing cost and now have 300mm diameter.

When compared to an 8 inch wafer, the 300mm wafer has 1.5 times bigger diameter and 1.2 times larger thickness, which derives 2 times higher internal shearing stress due to its own weight. This shearing stress, combined with the increase in the internal stress due to the non-uniform temperature on the wafers owing to the larger diameter, causes the wafer to have more crystalline defect (slip).

Current semiconductors are also required to have higher film performance accompanied by higher integration and minuteness. As a result, semiconductor furnaces now need to meet much severer requirements for heat control.

Temperature control of semiconductor furnaces is done mainly by PID control. However, current requirements for more sophisticated temperature control calls for other control methods such as H_∞ (H infinity) control which is fully based on modern control theories to satisfy such severe requirements[1) 2)]. Modern control theories, however, have problems, in that it is difficult to be understood by field engineers and control parameters cannot be adjusted separately. As a result, PID control is still being used by many makers and users because the PID control provides superior conformity to practical fields.

In view of the above, the authors improved the temperature control performance of the PID control significantly without losing the advantage of the PID control of the high conformity to practical fields by using the fuzzy inference for the transient response portions after reconsidering the conventional PID tuning method requiring a number of man-hours.

2. Problems of Heat Treatment Technique for Wafer

Figure 1 shows the structure of a vertical furnace (VF-5700B) used for the experiment.

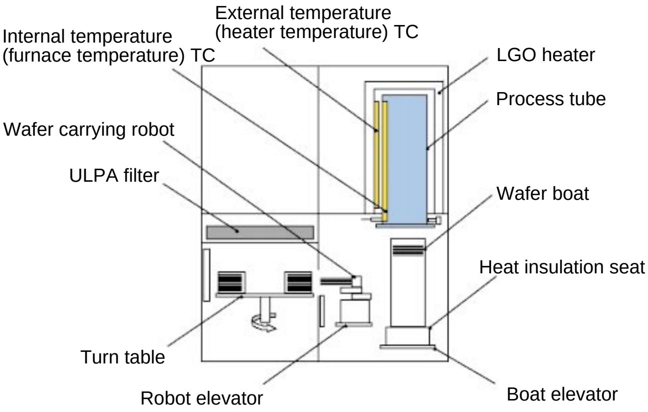


Fig. 1 Structure of vertical furnace

Thermal process is performed in accordance with the thermal process program called recipe under the procedure described below.

① Stand-by: The furnace is kept at the stand-by temperature so that the furnace is ready for wafer loading.

② From wafer loading to temperature recovery: Wafers of room temperature are introduced into the furnace at the stand-by temperature (then the wafer boat shown in **Fig. 1** is raised to enter the wafer into the process tube). At that time, the furnace temperature falls rapidly. It is important to reduce this temperature fall and to recover the temperature fall as soon as possible.

③ Ramping: While the wafers are in the furnace, the furnace temperature is raised to the processing temperature with the indicated ramping rate. During the temperature ramp, Temperatures of each zone must be uniform because temperature deviation among zones in the furnace may cause quality dispersion.

④ Stabilization for processing temperature: After the ramping operation to the predetermined temperature, the recipe has a fixed temperature. However, the existence of wafers in the furnace causes a high time constant and it becomes difficult for the furnace to follow the temperature that is indicated by the recipe. This causes temperature overshoot or round-shoulder-shape temperature response and the stabilization time for processing temperature is delayed.

⑤ Temperature fall: After the processing is finished, the furnace temperature is gradually lowered to the temperature appropriate for unloading the wafers.

In the above process, mainly the steps ②, ③, and ④ have a problem in the heat control. In other words, how to provide fast and accurate temperature stabilization to the each step of ②, ③, and ④ determines the throughput and wafer film performance, and heat treatment quality.

In addition to these performance specifications, tuning of PID parameters is also important. Conventionally, PID parameters have been normally set at each control phase of the above steps ① to ⑤. Thus, the adjustment of the start-up of the furnace and the readjustment due to the characteristic change of heater resultiny from long operating hours required a number of man-hours. Therefore, for the present development, reducing man-hours for tuning is also important in addition to solving the problems in performance.

3. Configuration of Control System

3. 1 Basic Configuration

The configuration of the control system is shown in **Fig. 2**.

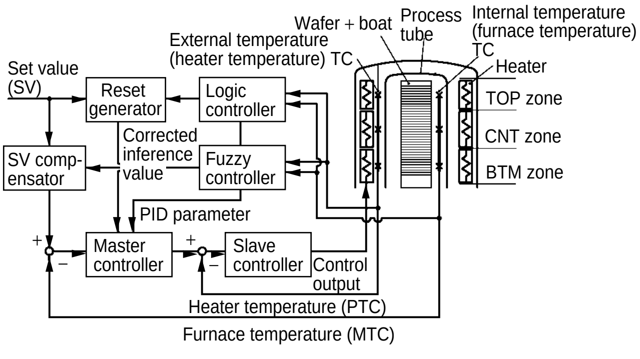


Fig. 2 Diagram of temperature control system

This control system is basically a cascade connection of PID controller and has the following functions.

① The master controller generates a set value (SV) for the slave controller and then the slave controller uses the SV to control the heater.

② The fuzzy controller changes the control parameters of the master controller depending on the control status to improve transient control characteristics. The fuzzy controller also generates the compensation value of SV.

③ The logic controller controls the flow of the control or the mode control (e.g., resetting the PID controller, signals for enabling or disabling the fuzzy inference).

④ The reset generation section which have received the signal from the logic controller sets the output value of the master controller to zero or a specified value.

⑤ The SV compensation part uses the fuzzy inference to generate a new SV for the purpose of inhibiting the overshoot caused when the ramping operation shifts to the steady control.

The VF-5700B used for the experiment consists of the three heat zones of TOP, CNT, and BTM, each of which is independently controlled. Thus, the control system shown in **Fig. 2** is actually composed of three control systems.

3. 2 Tuning of PID Parameters

Conventionally, tuning of PID parameters has required a complicated operation in which tuning is provided while confirming the link between the internal temperature (furnace temperature) and the external temperature (heater temperature) at each control phase.

By loading full power to the heater to estimate parameters based on the temperature response characteristics, the authors tried to eliminate these complicated tuning operations by such trial-and-error operations so that only a single parameter is determined.

Figure 3 shows the temperature rise characteristics of the internal and external temperatures. For the curves, the following model was used for the approximation.

External temperature: $\theta_{PTC}(s) = \dfrac{K_{PTC}}{(1+T_{HEATER}\cdot s)(1+T_{PTC}\cdot s)}U(s)$

Internal temperature:

$$\theta_{MTC}(s) = \frac{K_{MTC}}{(1+T_{HEATER}\cdot s)(1+T_{PTC}\cdot s)(1+T_{MTC}\cdot s)}U(s)$$

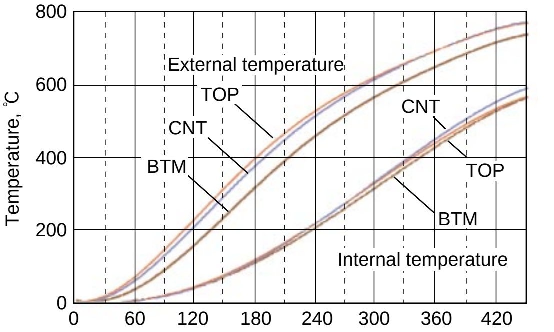


Fig. 3 Temperature rise characteristics of furnace

The curves for the high temperature show that the furnace seemed to have entered into a saturation operation once and then has an almost linear temperature rise, resulting in small difference between the internal temperature and the external temperature.

This model can be conceivably used to determine a parameter by simulation. However, the authors tried another method where the conformity to practical fields was taken into consideration to link the simulation result and the actual apparatus experiment to a graphical tuning method corresponding to the Ziegler-Nichols method, thus standardizing the parameter setting method. This allows the parameter tuning operation to require only two steps of applying a full power to obtain the temperature rise characteristics and correcting the overshoot as described below.

The result of control by PID using the parameters thus obtained is shown in **Fig. 4**.

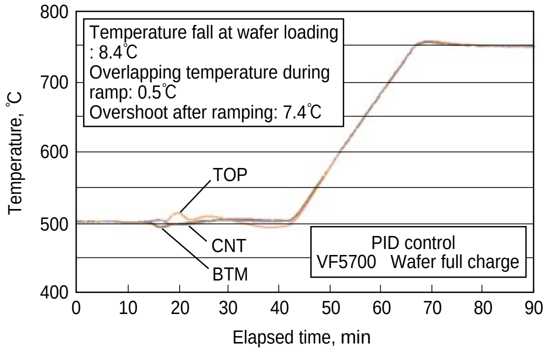


Fig. 4 Result of temperature control with PID controller

In this control result, temperature fall during the wafer loading was relatively small but an undercut after the overshoot of TOP was large and CNT and BTM also had an overshoot of about 4℃ at the recovery. The overshoot after the ramping was also large. However, the other portions had no problems. Thus, it is clear that the improvement of these transient responses provides sufficient control performance.

3. 3 Improvement of Temperature Recovery at Wafer Loading Characteristics

Figure 5 shows the boat loading at a stand-by at 160℃. The measurement was performed by turning on loading signals and turning off the power of the heater at the same time.

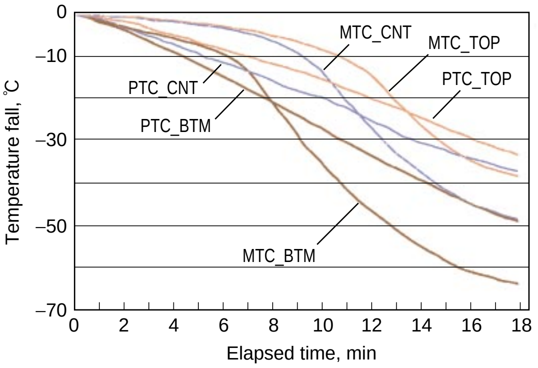


Fig. 5 Temperature change during wafer loading

As can be seen from this figure, temperature fall is caused by the flow-in of outside air immediately after the opening of the furnace and rapid temperature fall is also caused when the tip end of the wafer reaches each zone.

This temperature fall largely fluctuates depending on the wafer loading temperature or the implementation status. The fluctuation of these heat loads appears in the rate at which the furnace temperature changes. By the PID derivative control action, a control output proportional to the temperature change rate is obtained. However, for a portion in which the temperature falls rapidly, such a proportional control output is not fast enough to catch up with such temperature fall. The portion subsequent to such rapid temperature fall also requires rapid reduction of the control output. Thus, the authors used the control deviation and the temperature change rate to control the rate time T_d using the fuzzy inference value G_d in accordance with the following formula (1).

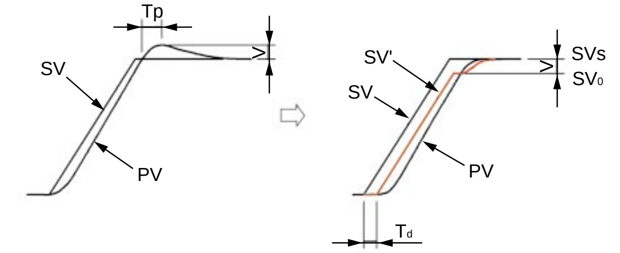
$$T_d = T_{d0} + (1 + G_d)\,\Delta T_d \quad \cdots\cdots (1)$$

Where, T_{d0}: differentiated time by tuning, G_d: fuzzy inference value ($-1 \leqq G_d \leqq 1$), ΔT_d: fluctuation range of the differentiated time.

3. 4 Inhibition of Overshoot

Since the temperature set value for the controller is provided to the controller by a higher-level component in the system, the controller itself does not have information such as a ramping rate or a final value. Thus, a method for inhibiting an overshoot based on a final set value could not be used. Therefore, the authors used a means for correcting the set value given from the recipe to provide the corrected value to the controller. In other words, a certain kind of set value filter was provided at the position in front of the master controller.

The details of the operation are shown in **Fig. 6**.



(a) Operation without SV compensation (b) With compensation of set value

Fig. 6 SV compensation method

Hereinafter, an overshoot at the PID control is assumed as V, current temperature as PV, time taken for overshoot peak from the PV exceeding a set value as Tp, set value given by the recipe as SV, output by SV compensator as SV', value at which the SV becomes constant (= final value at ramping) as SVs, and SV_0 as $SV_0 = SVs - V$.

The values of V and Tp are abtained by the control result from PID (**Fig. 4**) and are given to the controller together with the delay time T_d.

When the temperature rise rate is assumed as R℃/min, then the value of T_d must be $T_d \geqq V/R$.

When the recipe enters into the ramping, then the SV compensator delays SV by the set time T_d.

However, when $SV = SVs$ and $SVs - SV' \leqq V$ hold,

then the SV compensator terminates the delay, resulting in $SV' = SV_0$.

Thereafter, the corrected set value SV' is controlled by using the fuzzy inference in accordance with the following formula.

$$\Delta V = (1 + GSV)\, V_0$$

$$SV' = SV_0 + \Sigma(\Delta V) \cdots\cdots (2)$$

Where, $V_0 = V/\,Tp$, and G_{sv} is the fuzzy inference value $(-1 \leqq G_{sv} \leqq 1)$.

The fuzzy rules are maintained at $SV' = SV_0$ for $PV \leqq SV_0$ $(G_{sv} = -1)$ so that SV' smoothly approaches SVs at $PV \fallingdotseq SVs$. Specifically, it is an approach that when the occurrence of overshoot is presumed, the set value is set to lower only V temporarily, and then returning the set value to an original value when a peak appears. The use of the fuzzy inference eliminates the need for preciseness for the setting of V and Tp and also eliminates the need for changing the setting of the values of V and Tp according to the operation conditions other than the calculated ones. The compensation is completed when $SV' \geqq SVs$.

3. 5 Fuzzy Controller

The fuzzy calculation becomes effective by the wafer loading signal or the SV compensation start signal. Based on the conditions of: the current temperature θ, the deviation "e" $= SV - \theta$, and the temperature change $d\theta/dt$, the fuzzy inference value G is calculated by applying each of the determined fuzzy rules and the membership functions. Then, the calculation results by the formulas (1) and (2) are sent to the master controller or the SV compensator.

The fuzzy inference value having a certain value or more causes no difference in the control even with the increase in resolution[3]. Thus, the consequent was set to use a simplified inference method using the singleton membership function.

4. Control Performance

Figure 7 shows the control result by the developed controller.

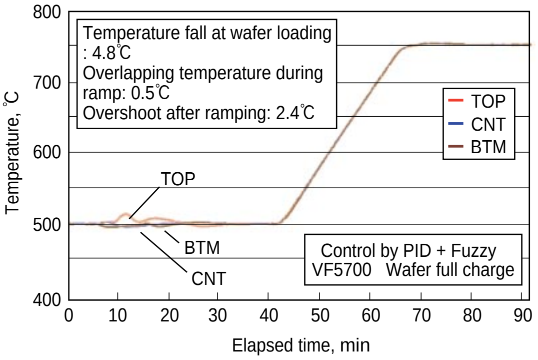


Fig. 7 Control result using developed temperature controller

During the wafer loading, the temperature in the TOP zone increases due to the heat affected by BTM and CNT zones in spite of the zero amount of control in the TOP zone. In this heat system, any more inhibition of the temperature fall of the BTM and CNT increases the temperature rise of the TOP, thereby causing a longer stabilization time in the whole system. This should be examined as a problem for the entire heat system.

However, when compared with the result shown in **Fig. 4**, the developed controller achieves significant reduction of the undercut after the overshoot in the TOP at the temperature recovery at wafer loading, and also eliminates the overshoot in the BTM and the CNT, showing the effects by the fuzzy control.

The performance of vertical furnaces using PID cascade control has been reported in various papers. **Table 1** shows the comparison between the performance by conventional cascade control by PID and that by the developed control system.

Table 1 Comparison between performance limit of PID[1] and the developed system

Item	PID	Developed
Overshoot after ramp, ℃	3.0 – 5.0	2.4
Ramp settling time, min	5 – 20	2 – 5
Overlapping temperature during ramp, ℃	3.0 – 5.0	< 0.5
Steady-state control, ℃	< ± 0.3	←
Initial setup time, day	3 – 10	1 – 1.5
Temperature fall at wafer loading, ℃	20[*]	5

[*] Result of conventional product (no available publicized data)

For obtaining the performance shown in **Table 1** by using a conventional PID control, a skilled operator frequently needed to do adjustment for a week or more. The developed controller, on the other hand, requires a mere one adjustment (for about six hours) to obtain the performance shown in **Fig. 7** and the right column of **Table 1**. This performance is similar to that obtained by the H_∞ control[2].

In the developed controller, the most of the adjusting time is the waiting time for the temperature to fall that has once been raised.

It was confirmed that the developed controller provided, without readjustment of PID parameters, similar control performance with the conditions of 160℃→350℃ and 350℃→500℃ in addition to 500℃→750℃, also when these three temperature conditions were used with filling wafers in half of the boat slots and gas flow rate of 50SLM.

5. Conclusion

By using the fuzzy inference, the portions requiring the transient response in the PID control were provided with a higher limit up to which PID can be applied. This enabled the significant improvement in the temperature control performance of the vertical furnace. Man-hours required for the tuning of the PID parameter, which has been a problem in the thermal process furnace, were also reduced significantly.

In this method, steady state characteristics are firstly secured to subsequently correct the transient response, therefore there is no conflict in tuning in which one portion is improved while another portion is worsened. When the method provides more accurate fuzzy rules and optimized scaling factors, the control accuracy is expected to increase further.

An issue as to whether a modern control or a classical control should be used for the development of a control system frequently arrives at an issue as to whether a user requires a parameter adjustment, unless an active characteristic to be controlled is complicated that much. What is important is how to increase a throughput with a process desired by a customer and how to reduce the downtime to zero even when an unexpected failure occurs.

Thus, the authors attempted the control system to be simple and intuitive as possible, so that the system would be easily used in production fields.

Although there are few approaches in which PID is normally used and the transient portions are assisted with the fuzzy control, this approach has an advantage which the conventional PI-type fuzzy control does not have, in that the identification of a system model in an approximate way provides the discussion of the stability or the response numerically. Although the control only with PID does not satisfy the required specification, the authors consider that the developed method may be one answer to a requirement that the easy-to-useness and the conformity to practical field provided by PID cannot be abandoned.

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