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PRECISE CONTROL METHOD OF TEMPERATURE RISING SPEED OF WAFER DURING RAPID THERMAL PROCESSING WITH LAMP HEATERS

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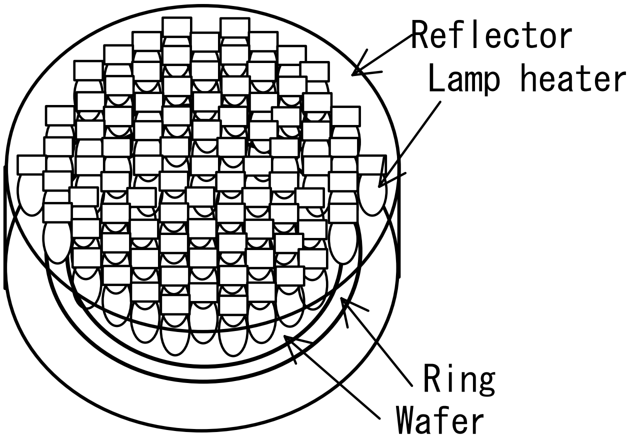
ABSTRACT

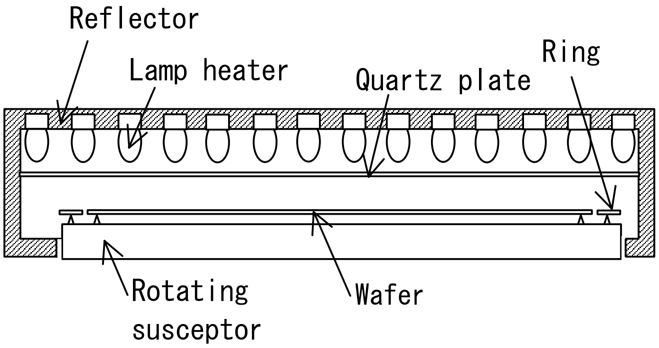
In rapid thermal processing of a semiconductor wafer, temperature-rising-time is the same order of heating-time, and so keeping a given temperature-rising-speed of the wafer during the temperature-rising process is important. We made an experimental apparatus to measure the temperature-rising-speed of a ceramic ball of 2 mm in diameter heated with four halogen lamp heaters. The temperature change of the ceramic ball was measured and the heating rate of the halogen lamp heaters was controlled by a personal computer to keep a given temperature-rising-speed 50°C/s with controlling-time-interval 0.1 s. We examined the effect of various heating control methods on the error of the temperature-rising-speed of the ceramic ball. We tested the PID-control, the control with a prepared correlation, and the combined method of control with prepared correlation and PID-control. We found that the combined method is a good method to decease the error of the temperature-rising-speed. The average error of the temperature-rising-speed is 0.5°C/s and the repetition error is almost zero for the temperature-rising-speed 50°C/s during 330°C to 370°C. We also measured the effects of artificial control-delay-time and measuring-error of the monitor temperature on the error of the temperature-rising-speed.

INTRODUCTION

In the heating process of manufacturing semiconductors, silicon wafers are heated to 900°C in order to diffuse impurity atoms (arsenic, boron, or phosphorus) into the silicon substrate and to oxidize it. Schematic views of a typical lamp heating apparatus are shown in Fig. 1. Many lamps are arranged on the upper side of a cylindrical apparatus. A silicon wafer is placed below the lamps and heated to 900°C. A shielding ring is placed around the wafer to produce uniform heating of wafer. Recent advances in VLSI technology incorporate shallow junctions and a thin oxidation film, which require rapid heating by lamp heaters for about ten seconds at about 900°C after heating-up rate of 100°C/s with lamp heaters. Temperature-rising-time is the same order of the heating-time, and so keeping the given temperature-rising-speed of



(a) Schematic view



(b) Vertical cross section

Fig. 1 Lamp heating apparatus

the wafer during the temperature-rising process is very important for uniform heating. On the other hand, surface condition of each wafer is different and unexpected disturbances occur during heating process. Therefore optimum heating control conditions are still determined by many experiments.

Some works on control methods of temperature distribution in wafers under lamp heating have been reported. Sorrell et al. [1] reported a simple heating control method using one-dimensional model. Norman [2] reported a dynamic heating control method of many independent lamp-heaters to minimize temperature distribution in the wafer. Aral et al. [3] reported optimum heating control method using local linear transforming function. Choi et al. [4] and Yang et al. [5] reported analytical and experimental works using learning approach for heating control of wafers. Lin et al. [6] reported accuracy of 0.8°C during temperature-rising process of 100°C/s by using inverse heat transfer method. The authors [7, 8, 9] studied the effects of the temperature monitoring positions and the number of heating zones on temperature distribution in the wafer. Also, the effects of various heating control methods on the error of the temperature-rising-speed of 100°C/s were examined with numerical simulation.

In the present work, the effects of various heating control methods on the error of the temperature-rising-speed of 50°C/s were measured experimentally. Also, the effects of the artificial control-delay-time and measuring-error of the monitor temperature on the error of the temperature-rising-speed were measured.

EXPERIMENTAL APPARATUS

Experimental apparatus is shown in Fig. 2. In this work, we measured temperature-rising-speed of a ceramic ball in a cylindrical apparatus. As it was difficult to measure precise temperature-rising-speed of a silicon wafer, we used a simple ceramic ball. The cylindrical apparatus is copper, 50 mm in diameter and 50 mm in height. Wall of the apparatus is cooled by water, and the inside surface was polished by a sand paper #2000. The ceramic ball is 2 mm in diameter and it is placed in a quart tube of 2.5 mm in diameter to reduce effect of air convection. The center temperature of the ceramic ball was measured by a K-type thermocouple of 0.2 mm in diameter, and it is used as a monitoring temperature in the control. Four lamp heaters are placed upper and lower parts of the apparatus. Total maximum power of the four-halogen lamp heaters is 1200 W. Controlling-time-interval is 0.1 s and the given temperature-rising-speed is 50°C/s. The heating rate of the halogen lamp heaters was controlled at each controlling-time-step using the monitoring temperature of the ceramic ball by a control system composed with a personal computer, a power controller and a thyristor. Average error of temperature-rising-speed, amplitude of oscillation, and repetition error were evaluated during 330°C to 370°C, which is most stable temperature-rising period for our experimental apparatus.

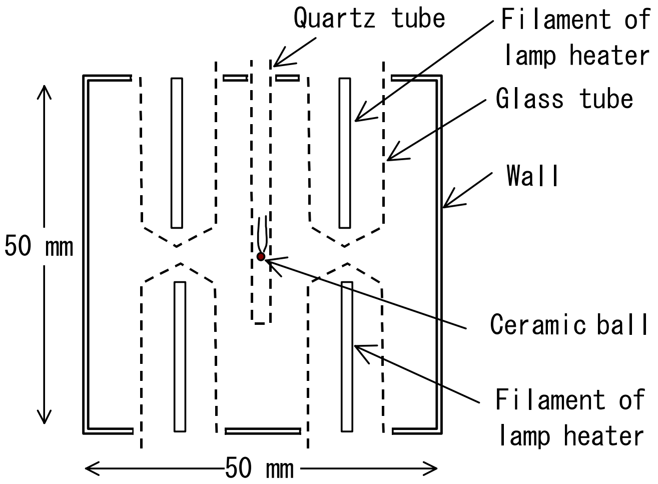


Fig. 2 Experimental apparatus

CONTROL METHODS OF TEMPERATURE-RISING-SPEED

In this work, five control methods are examined. Method (A) is the PID-control of heat generation using temperature difference ΔT between the given temperature and the monitoring temperature. The given temperature is a function of time. Heat generation is calculated by following equation using temperature difference ΔT as the parameter ΔX.

$$Q = Q_{\max} P\left(\Delta X + \frac{\int(\Delta X)dt}{I} + D\frac{d(\Delta X)}{dt}\right) \tag{1}$$

where, P, I, D are constants, and $Q_{\max}$ is maximum heat generation. Optimum PID constants were determined by advance experiments as P=0.0075 K^{-1}, I=1 s, and D=0.1 s. The PID-control is the most popular control method.

Method (B) is the PID-control using the difference of the given temperature-rising-speed and the monitoring temperature-rising-speed. Heat generation is calculated by Eq. (1) using the difference of the temperature-rising-speed as the parameter ΔX. Optimum PID constants were determined by advance experiments as P=0.001 s/K, I=0.1 s, and D=0.01 s.

Method (C) is the control method of heat generation with a prepared correlation among temperature, heat generation, and temperature-rising-speed. The correlation is obtained in advance experiments with constant powers of heat generation at every 10% from 10% to 80% of the maximum power. The 80% of the maximum power of lamp heaters was the allowable maximum capacity of the thyristor in our experimental apparatus. Fifth order correlation equation is obtained with the method of least squares. This is a simple method of the learning control method.

Method (D) is the combined method of control with the prepared correlation (method (C)) and the PID-control using temperature difference (method (A)). Heating rate was obtained by multiplication of both control values. Optimum PID constants were determined by advance experiments as P=0.00003 K^{-1}, I=100 s, and D=0.001 s.

Method (E) is the combined method of control with the prepared correlation (method (C)) and the PID-control using difference of temperature-rising-speed (method (B)). Optimum PID constants were determined by advance experiments as P=0.0000025 s/K, I=0.1 s, and D=0.01 s.

EXPERIMENTAL RESULTS OF EFFECT OF CONTROL METHODS ON ERROR OF TEMPERATURE-RISING-SPEED

Figures 3 and 4 show experimental results of the temperature changes, and Figs. 5, 6 and 7 show the temperature-rising-speed for the methods (A)-(E). Table 1 shows the average error of temperature-rising-speed, amplitude of oscillation, and repetition error for various control methods during 330°C to 370°C. In Table 1, we can find that the average error of the method (B) is large, and the repetition error of the method (C) is large. Average error of the temperature-rising-speed is small as 0.5°C/s for the methods (D) and (E) during 330°C to 370°C. Their repetition errors are almost zero, because the control methods worked well. The combined methods (D) and (E) of control with the prepared correlation and the PID-control are good methods to decease the error of temperature-rising-speed, because main heating rate is determined by the correlation and noise errors are reduced by the PID-control. In this work we evaluated the temperature-rising-speed during 330°C to 370°C, and the results are similar to other temperature range.

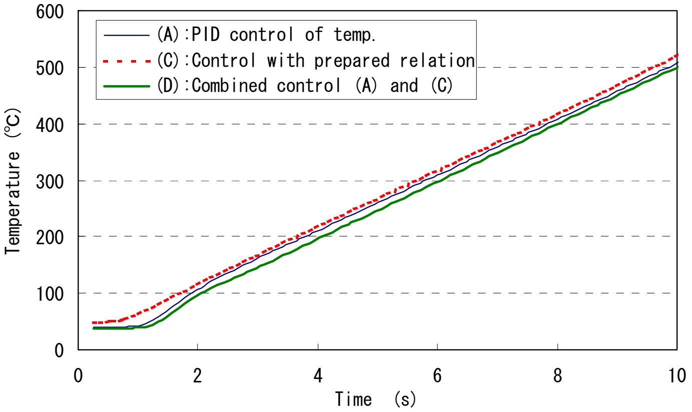


Fig. 3 Temperature change for (A), (C) and (D)

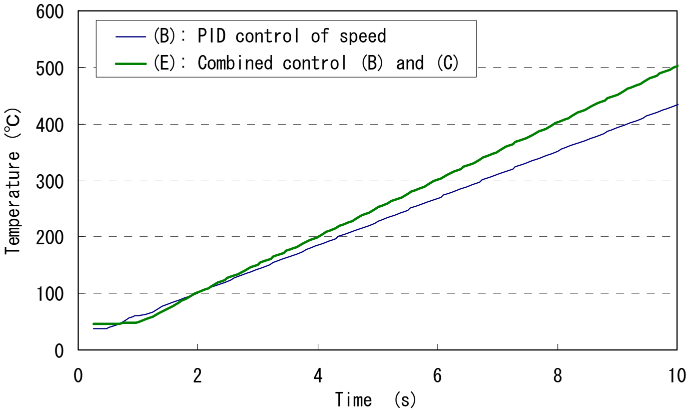


Fig. 4 Temperature change for (B) and (E)

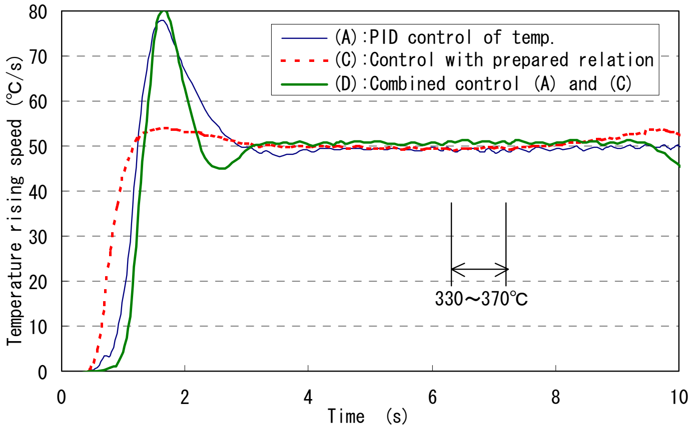


Fig. 5 Temperature-rising-speed for (A), (C) and (D)

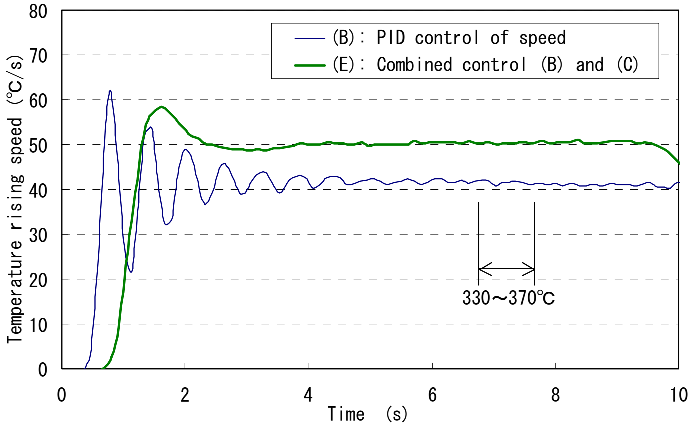


Fig. 6 Temperature-rising-speed for (B) and (E)

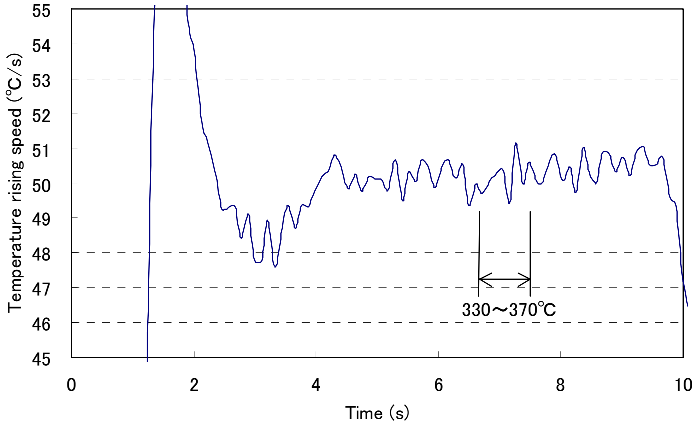


Fig. 7 Temperature-rising-speed for (E)

EFFECT OF CONTROL-DELAY-TIME AND MEASURING-ERROR ON ERROR OF TEMPERATURE-RISING-SPEED

In actual control system, there are control-delay-time and measuring-error of the monitor temperature. We measured the effects of artificial control-delay-time of 0.1 s and artificial measuring-error of ±0.5°C at each controlling-time-interval 0.1 s on the error of the temperature-rising-speed. The given temperature-rising-speed is 50°C/s. Figures 8 and 9 show the temperature-rising-speed for the method (E) of control with the prepared correlation and the PID-control with artificial control-delay-time of 0.1 s and artificial measuring-error of ±0.5°C. Table 2 shows experimental results of the effect of the control-delay-time and the measuring-error of the monitor temperature on error of temperature-rising-speed for various control methods during 330°C to 370°C. The values of the change of average error in Table 2 show difference from the temperature-rising-speed without the control-delay-time and the measuring-error. We can find that effect of control-delay-time of 0.1 s is not so large, because it is less than delay of temperature response of our experiment, which is about 0.4 s as shown later. The change of average error of the method (C) is as large as the repetition error shown in Table 1. Estimated error of the temperature-rising-speed by the effect of artificial measuring-error of ±0.5°C with controlling-time-interval 0.1 s is ±5°C/s. Effect of measuring-error of monitor temperature is small for the methods (D) and (E). The measuring-error of ±0.5°C increases amplitude of oscillation 1.5°C/s for the method (E) (Fig. 9). It is less than the estimated error (±5°C/s) because of the control.

EFFECT OF CHANGE OF GIVEN TEMPERATURE-RISING-SPEED

Next, we measured effect of change of given temperature-rising-speed during process. It is sometimes required in actual manufacturing process. The given temperature-rising-speed changed from 50°C/s to 25°C/s at 275°C and from 25°C/s to 50°C/s at 325°C in our experiments. Figures 10 and 11 show experimental results of the temperature change and the temperature-rising-speed for the method (E) of control with the prepared correlation and the PID-control. The right column of Table 2 shows effect of changing the given temperature-

Table 1 Errors of temperature-rising-speed for various control method during 330°C to 370°C

	Average error	Amplitude of oscillation	Repetition error
(A): PID-control of temperature	0.9°C/s	1.1°C/s	< 0.1 °C/s
(B): PID-control of speed	6.6°C/s	0.5°C/s	< 0.1 °C/s
(C): Control with prepared correlation	0.5°C/s	1.0°C/s	5 °C/s
(D): Combined control (A) and (C)	0.5°C/s	0.8°C/s	< 0.1 °C/s
(E): Combined control (B) and (C)	0.3°C/s	1.0°C/s	< 0.1 °C/s

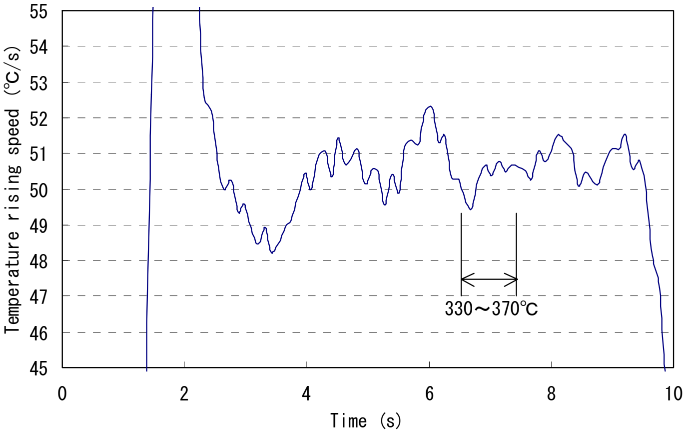


Fig. 8 With artificial control-delay-time 0.1 s for (E)

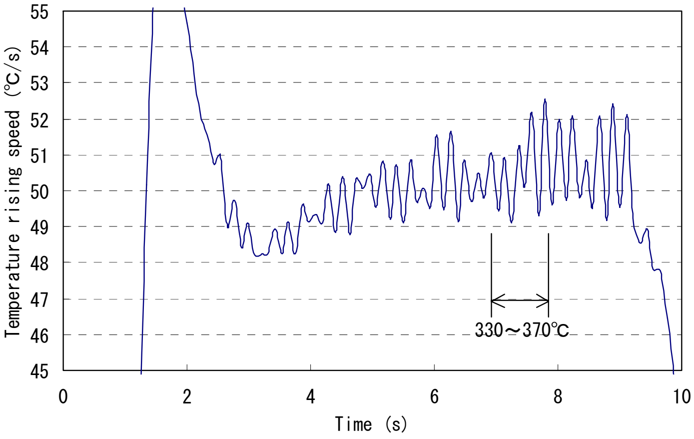


Fig. 9 With artificial measuring-error ±0.5°C for (E)

Table 2 Effects of control-delay-time, measuring-error of monitor temperature, and changing target speed on error of temperature-rising-speed

	Effect of control-delay-time of 0.1 s		Effect of measuring-error of monitor temperature ±0.5°C		Change target speed
	Change of average error	Ampli. of oscil.	Change of average error	Ampli. of oscil.	Ampli. of oscil.
(A)	+0.1°C/s	0.6°C/s	+0.2°C/s	1.5°C/s	3°C/s
(B)	+0.2°C/s	1.0°C/s	+2.2°C/s	1.5°C/s	1°C/s
(C)	-2.1°C/s	1.0°C/s	-5.6°C/s	0.5°C/s	1°C/s
(D)	+0.1°C/s	1.0°C/s	-0.4°C/s	1.0°C/s	5°C/s
(E)	+0.3°C/s	1.0°C/s	+0.2°C/s	1.5°C/s	3°C/s

rising-speed on error of temperature-rising-speed for various control methods during 330°C to 370°C. We can find delay of temperature response is about 0.4 s (Fig. 11) and amplitude of oscillation of error is 3°C/s for the method (E).

SUMMARY

We examined the effect of five heating control methods on the error of the temperature-rising-speed of 50°C/s. Following results were obtained.

1. The combined methods ((D) and (E)) of control with the prepared correlation and the PID-control are a good method to decease the error of the temperature-rising-speed. The average error of the temperature-rising-speed is 0.5°C/s and the repetition error is almost zero during 330°C to 370°C.

2. We measured the effects of artificial control-delay-time of 0.1 s and artificial measuring-error of ±0.5°C at each controlling-time-interval 0.1 s on the error of the temperature-rising-speed. The measuring-error of ±0.5°C increases the amplitude of oscillation of error 1.5°C/s for the combined method (E).

3. When the given temperature-rising-speed changed from 50°C/s to 25°C/s, the amplitude of oscillation of error is 3°C/s for the combined method (E).

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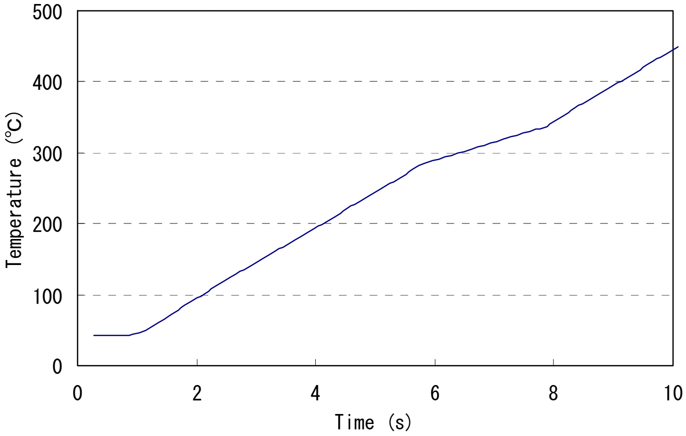

Fig. 10 Temperature change with changing speed

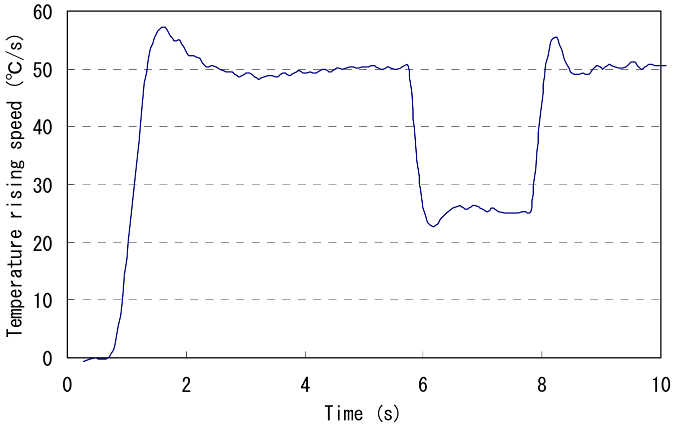

Fig. 11 Temperature-rising-speed with changing speed

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