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Improvement in wafer temperature uniformity and flow pattern in a lamp heated rapid thermal processor

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Abstract

An experimental lamp heated, rapid thermal processor (RTP) for an 8-in single silicon wafer was designed and established to investigate the thermal and flow characteristics in the processing chamber by transient temperature measurement and flow visualization. Experiments were carried out to explore the effects of placing a highly conducting copper plate right below the wafer on the uniformity of the wafer temperature and effects of the showerhead on the resulting flow distribution in the processing chamber. The measured data indicated that adding the copper plate can effectively reduce the nonuniformity of the wafer temperature. Besides, using a showerhead with finer holes in it results in a better flow distribution in the processor. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The recent continuing miniaturization of integrated circuit (IC) components and increasing functions of a single IC chip have called for an ultra-high integration of the IC components in a single large wafer. Due to their fast ramp-up and ramp-down rates lamp heated, single wafer processors are preferred in this ultra-high IC integration. However, successful fabrication of the extremely dense submicron circuits on a large wafer still faces the problems of the temperature nonuniformity on the wafer and bad flow distribution in the vicinity of the wafer, among others.

In the design of a lamp heated, rapid thermal reactor, Özturk et al. [1] proposed that for getting a uniform thin film, the thickness of the velocity, temperature, and concentration boundary layers over the wafer must be uniform, the wafer temperature should be uniform and the gas flow in the reactor must be free of any laminar vortices. The higher radiative loss from the wafer edge was found to result in a radial temperature gradient in the wafer [2,3]. This temperature gradient induces a thermal stress which is compressive in central region of the wafer but is tensile towards the edge of the wafer, as noted by Sorrell et al. [4]. They further indicated that it was difficult to produce the desired

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Nomenclature

D_p	processor diameter
Q_j	total air volume flow rate entering the processor
Re_p	Reynolds number based on the processor diameter ($= V_\mathrm{in} D_\mathrm{p}/\nu$)
t	time
T_wf	wafer temperature
V_in	average velocity of the air at the inlet of the processing chamber

Greek letters

ν	kinematic viscosity of air
ϕ	injection angle measured from the tangent to the perimeter of the mixing chamber

irradiance distribution in a rapid thermal processor (RTP) by employing only the flat reflector. Focusing reflectors can be used to improve the temperature uniformity. They also proposed to arrange the heating lamps into concentric heating zones. In a numerical study, Campbell et al. [5] gave a two-dimensional solution to the recirculating flow in a RTP reactor including the convective gas flow effect.

Nenyei et al. [6] found that multiple gas baffle system, low-temperature guard ring surrounding the wafer, and independent top and bottom heater bank control were important in optimizing the gas flow in the processing chamber. To improve the wafer temperature uniformity, a cone-shape shield was placed at the edge of the wafer to reduce the heat loss from the edge and to reflect the radiative energy back into the wafer [7,8]. Cho and Kim [9] used a ring of silicon dioxide formed at the wafer edge to reduce the heat loss from the edge. Zöllner et al. [10] showed that the peripheral temperature drop could be compensated by a separate focusing lamp ring. Another way to reduce the edge effect is to provide a supplementary heat source surrounding wafer [11,12]. A passive guard ring such as an independent heated ring [13] or an annual lamp [14] was noted to improve the wafer temperature uniformity. Moreover, the guard rings can reduce the temperature-gradient-induced wafer deformation by a factor of 10 when compared to a free-standing wafer [15]. Recently, Lee et al. [16] used concentric Si rings on a planar quartz or Si susceptor to improve the wafer temperature distribution.

The uniformity of the wafer temperature may also result from the local differences in the radiation absorption and emissivity of the wafer surface induced by the pattern on the wafer [17,18]. Vandenabeele et al. [19] showed that the patterned oxide layers could cause the wafer temperature nonuniformity up to 80 K.

The above literature review clearly indicates that the flow and thermal characteristics in a rapid thermal processor for a single wafer remain largely unexplored especially for a large wafer during the transient stage. Moreover, methods to improve the temperature uniformity of the wafer still need to be sought. In the present study an experimental rapid thermal processor for an 8-in silicon wafer is established to investigate the flow and thermal characteristics associated with the processor through the flow visualization and transient temperature measurement. Attention is focused on the possible improvement of the wafer temperature uniformity by placing a high-conductivity copper disk below the wafer and on the effects of the showerhead on the gas flow distribution in the processor.

2. Experimental apparatus and procedures

The experimental apparatus established in the present study schematically shown in Fig. 1

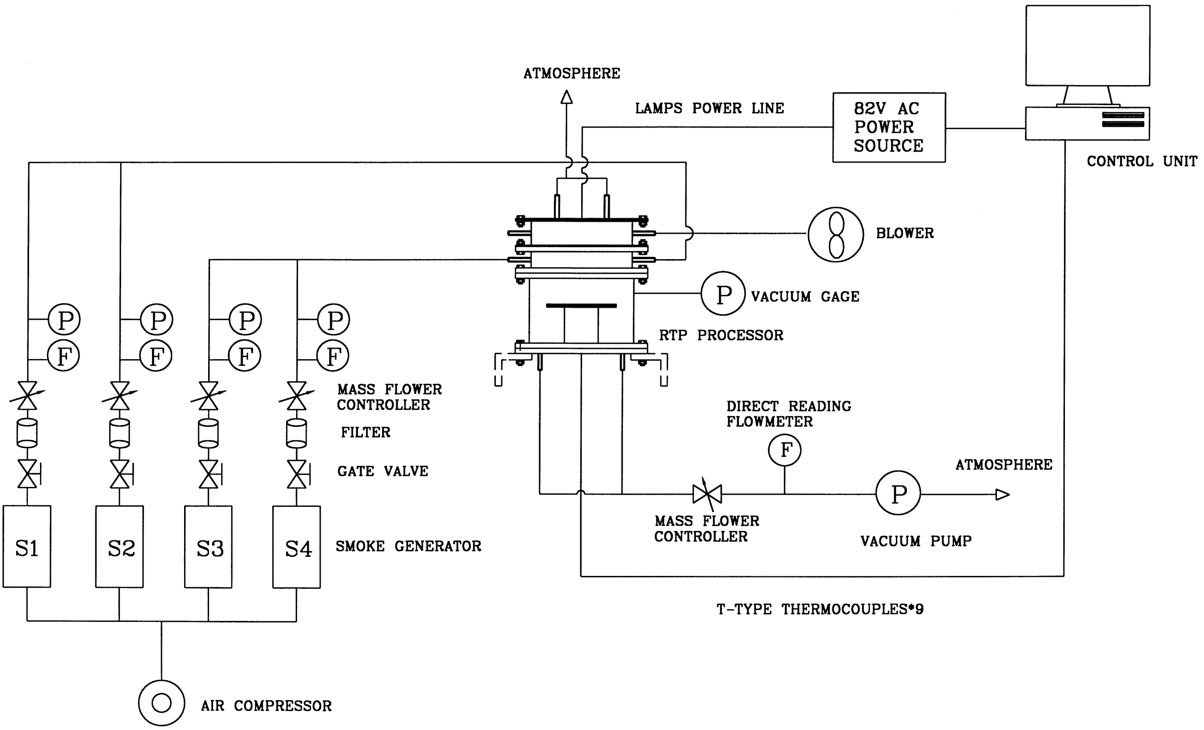

Fig. 1. Schematic diagram of the experimental apparatus.

consists of six major parts, namely, the heating lamp unit, gas injection unit and mixing chamber, processing chamber, vacuum system, temperature measurement and data acquisition system, and control unit. Note that air is used as the working fluid to replace the inert gases normally used in the real rapid thermal processing.

The lamp heating unit includes 13 410W & 82V OSRAM tungsten–halogen lamps, which are arranged into two zones, an inner ring of four lamps and an outer ring of nine lamps. The input power to each zone can be adjusted for the optimal control of the wafer temperature uniformity.

The gas injection unit consists an air compressor, a flow meter, four smoke generators, four solenoid flow control valves, filters, pressure regulators and injection nozzles. The installations of the smoke generators allows for the visualization of the gas flow in the processor. Compressed air is injected into the mixing chamber through the four injection nozzles located at the side wall of the mixing chamber. The air is then mixed in the mixing chamber and moves across the showerhead into the processing chamber. The showerhead is a thin perforated circular quartz plate of 4 mm thick. It contains 385 small circular holes of having the same diameter of 6 mm. Another showerhead with 2401 finer holes of having the same diameter of 2 mm is also tested. Moreover, a single vertically downward air jet leading into the processor through a connection pipe and directly impinging onto the wafer has been tested to access the resulting flow pattern in the processing chamber. In this jet impinging experiment no gas is injected into the mixing chamber from the nozzles on its sidewall.

The processing chamber is cylindrical and has an outside diameter of 30 cm. Its side wall is made of 7 mm thick Pyrex glass. The wafer is leveled horizontally and fixed centrally. A copper plate of 2 mm thick is placed just below the wafer to provide an additional heat transfer path. Five type-T thermocouples are stuck at the back of the wafer at selected locations and three other thermocouples of the same type are stuck on the copper plate. Note that these thermocouples are positioned at three concentric circles at an equal radial interval of 5 cm.

The vacuum system consists of a rotary vacuum pump with a 50 standard liter per minute (SLPM) pumping capacity. The pumping rate can be adjusted by a manual flow control valve. The system pressure of the chamber is maintained at the required level by adjusting the flow rate of the vacuum pump.

An on/off control algorithm, which is found to perform better than linear proportional control, is used to control the input power to the lamps. The measured average wafer temperature is calculated by the computer to check whether it is over or under the set temperature. The result is then used to drive a stepping motor which, in turn, connects with a variable resistor and thus can control the required electric current from the power supply. Thus, the input power to the lamps is adjusted.

For clarity, the schematic diagram of the processing chamber is shown in Fig. 2. The test starts with the air at room temperature T_a injected into the mixing chamber. Meanwhile, the lamps are turned on until the wafer temperature reaches to the preset level. The air streams mix in the mixing chamber and then move across the showerhead into the processing chamber. It flows over the wafer and is finally sucked out of the chamber through the exhaust ports. For a single jet impinging test the air is directly introduced into the processing chamber through an inlet pipe of 8 mm in inner diameter and the showerhead is replaced by a non-perforated quartz plate. After the flow reaches steady or statistically stable state, we begin the flow visualization and temperature measurement. The gas flow pattern in the chamber is illuminated by a vertical plane light sheet from a laser sheet generator and is photographed by a camera from the chamber side.

3. Experimental results and discussion

In this study we fixed the distance between the showerhead or single-tube outlet and the wafer surface at 10 cm. Besides, the chamber pressure is fixed at 1 atm. The experimental results are presented to illustrate the effects of the copper plate on the uniformity of the wafer temperature and the effects of the showerhead on the resulting flow distribution.

3.1. *Effects of copper plate on the wafer temperature uniformity*

In order to improve the temperature uniformity of the wafer, we have designed a nearly isothermal plate, which is made of high thermal conductivity copper with its upper surface coated with black paint, and placed it beneath the wafer with 1 cm apart (Fig. 2(b)). To compensate the higher energy loss from the wafer edge, another copper plate with an outer thin flange acting as a guard ring is also tested.

The maximum temperature differences across the wafer deduced from the thermocouple data measured at the five selected locations on the wafer (Fig. 2(c)) during the entire ramp-up and ramp-down processes without placing the copper plate below the wafer for the processor with a single inlet pipe for the limiting case with $Q_j = 0$ are shown in Fig. 3 for three preset temperature levels for the wafer. Initially at $t < 0$, the whole apparatus is at room temperature T_a. The time $t = 0$ denotes the instant at which the lamps are simultaneously turned on. The results indicate that the ramp-up rate of the wafer temperature is rather slow at about 2–3°C/s. It takes about 50 s for the wafer to reach the preset temperature and then the wafer stays at the preset temperature with certain level of fluctuation. At $t = 1200$ s the lamps are turned off and the wafer temperature declines gradually. The results show that the maximum temperature differences at the end of the heating cycle ($\Delta T_{\max}$) are 4.8, 8.2 and 10.5°C respectively corresponding to the wafer set at 100, 150 and 200°C. When the copper plate without flange is placed under the wafer with the other parameters fixed at the previous values, the ramp-up rate of the wafer temperature is slightly lower. But the maximum temperature differences across the wafer reduce respectively to 4.0, 4.8, and 7.2°C. For air injected into the processor at constant flow rates of 1–5 SLPM, the results for T_{wf} set at 100°C suggested that the maximum temperature

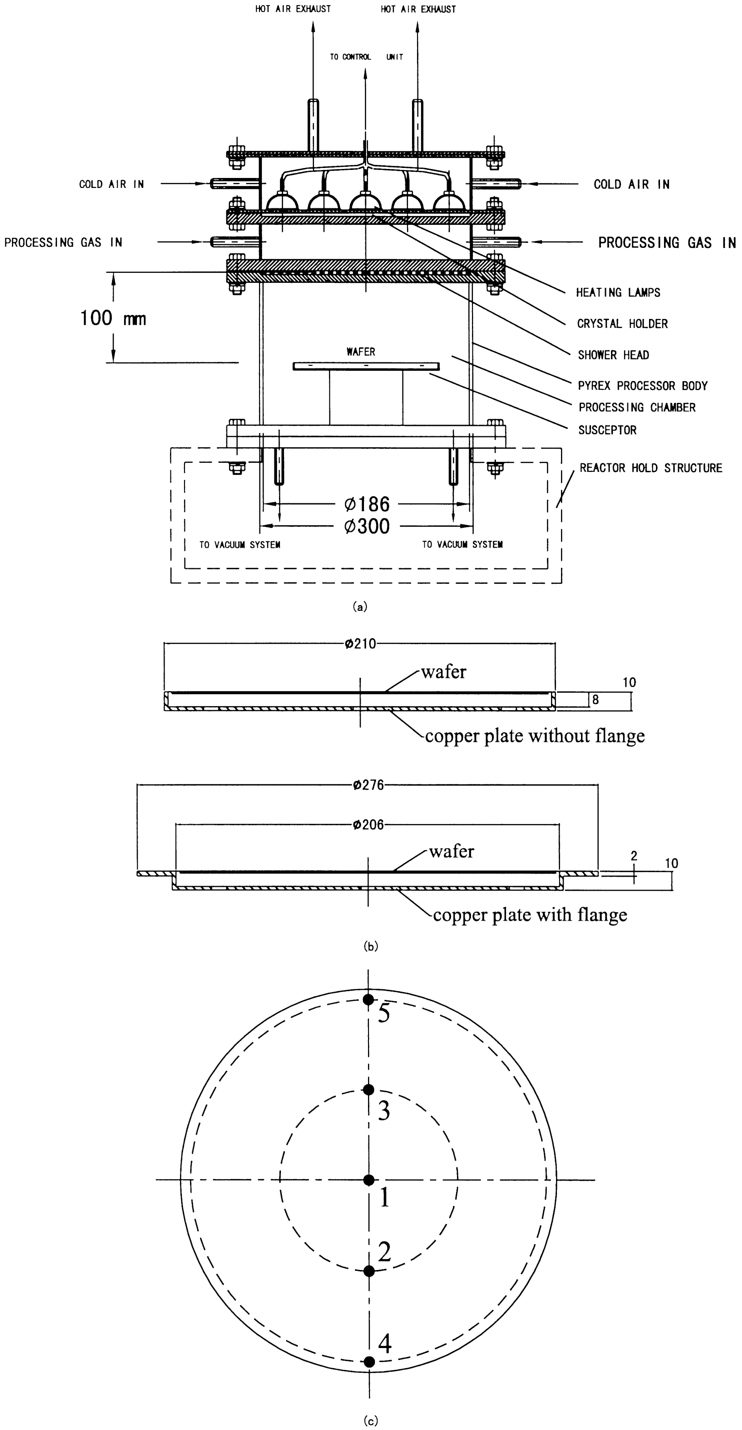

Fig. 2. Schematic diagrams of the processor (a), copper plate without and with flange (b) and location on the detection points the wafer (c).

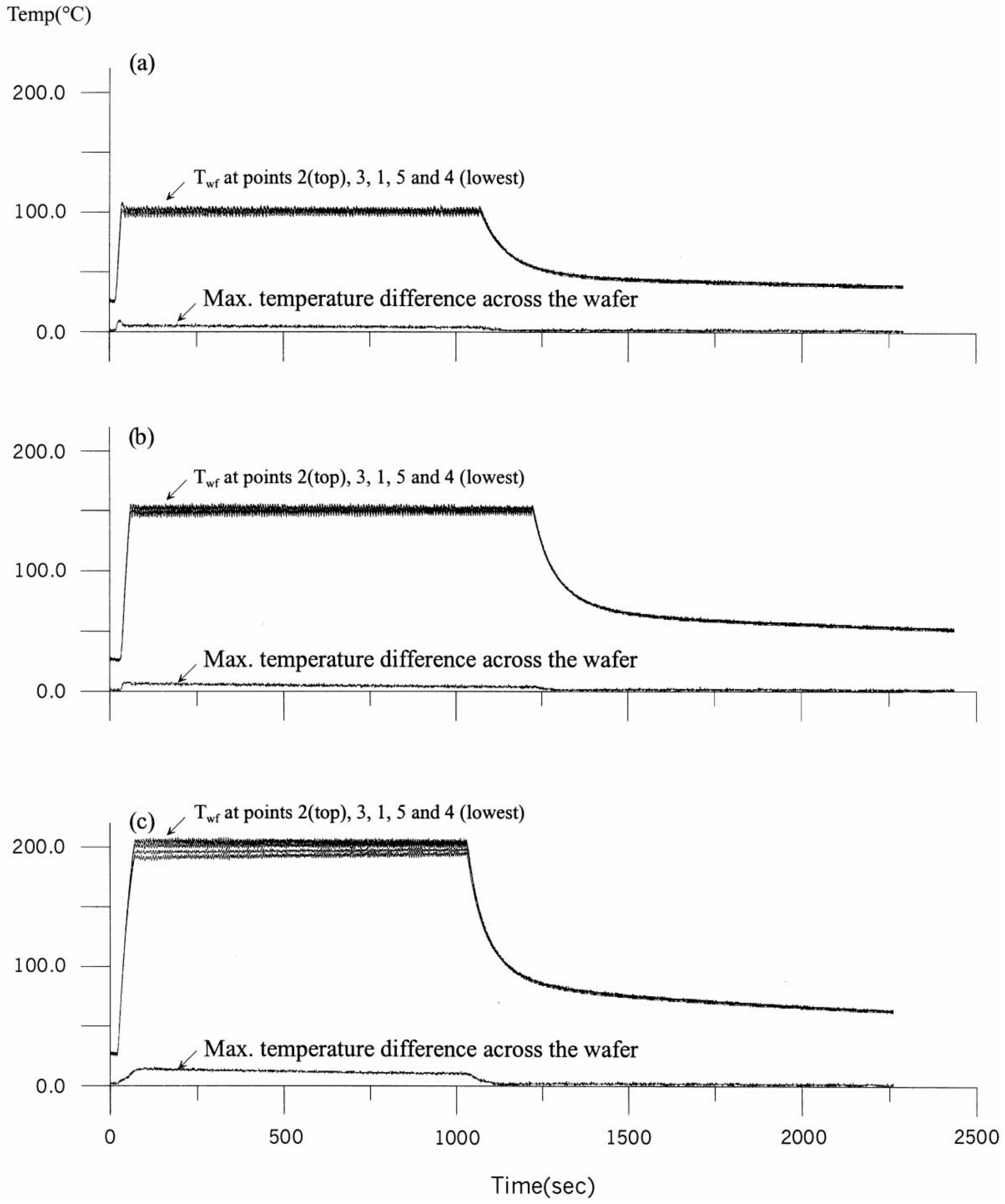

Fig. 3. The wafer temperature and the maximum temperature difference across the wafer during the entire heating process for $Q_j = 0$ without copper plate for the wafer setting temperature of (a) 100, (b) 150 and (c) 200°C.

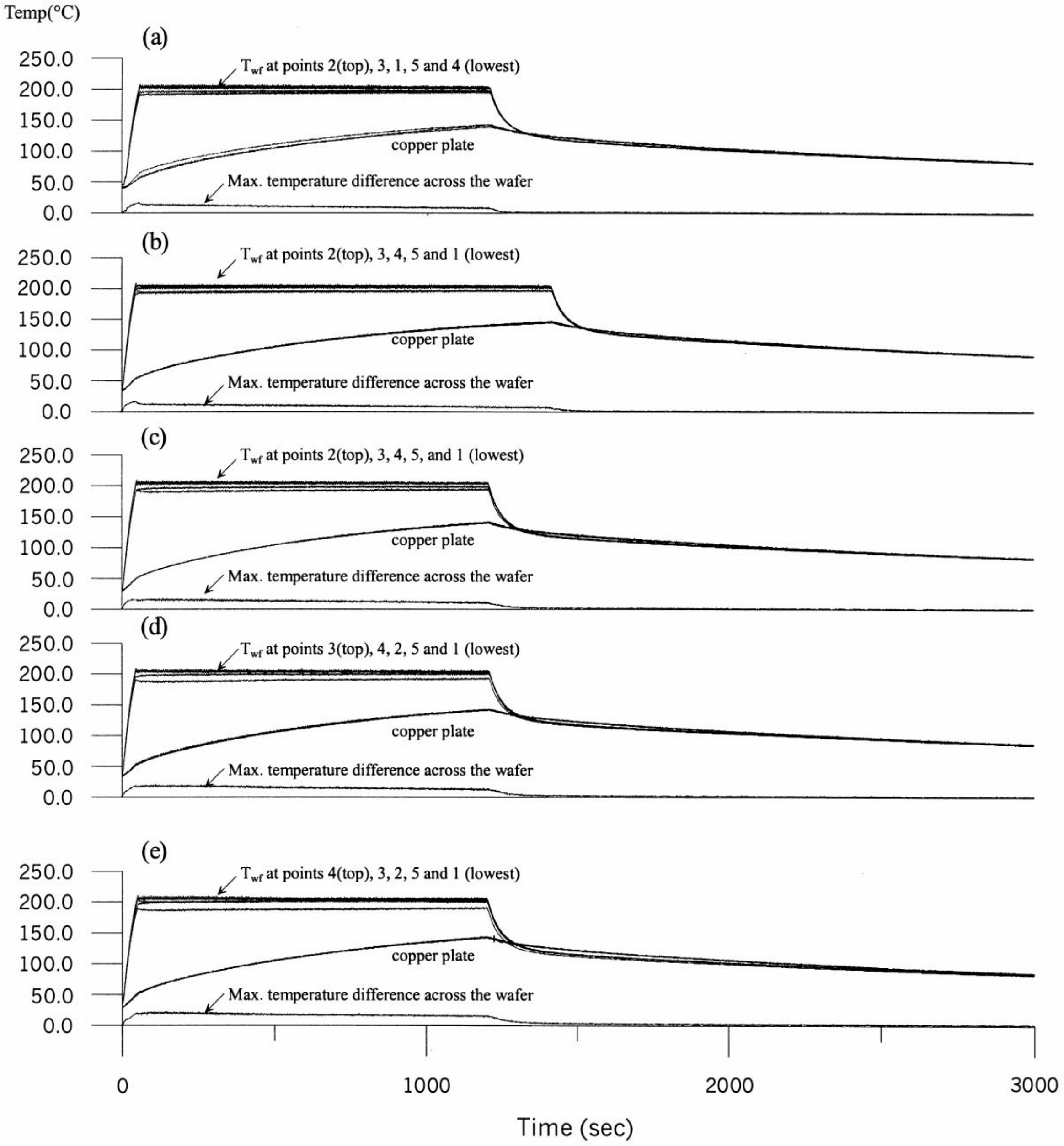

Fig. 4. The wafer and copper plate temperatures at selected points and the maximum temperature difference across the wafer during the entire heating process for $T_{\mathrm{wf}} = 200°\mathrm{C}$ for (a) $Q_j = 0\,\mathrm{SLPM}$, (b) $Q_j = 1\,\mathrm{SLPM}$, (c) $Q_j = 2\,\mathrm{SLPM}$, (d) $Q_j = 3\,\mathrm{SLPM}$ and (e) $Q_j = 5\,\mathrm{SLPM}$.

difference is larger for a higher flow rate and is higher than that for $Q_j = 0$. Note that at higher wafer setting temperature for $T_{\mathrm{wf}} = 150$ and $200°\mathrm{C}$ the maximum temperature differences for $Q_j = 1$–5 SLPM are also all above that for $Q_j = 0$ except for $Q_j = 1\,\mathrm{SLPM}$ at $T_{\mathrm{wf}} = 200°\mathrm{C}$ (Fig. 4). It is noted from these data that the higher flow rate produces a larger $\Delta T_{\max}$. The larger $\Delta T_{\max}$ for a higher gas

Table 1
Maximum temperature differences across the wafer at the end of the heating process for wafer set at different temperatures and different inlet gas flow rates

Q_j (SLPM)	T_{wf} (°C)		
	100	150	200
(a) *Copper plate without flange*			
0	$\Delta T = 4.0$	$\Delta T = 4.8$	$\Delta T = 7.2$
1	$\Delta T = 4.1$	$\Delta T = 6.0$	$\Delta T = 7.0$
2	$\Delta T = 5.0$	$\Delta T = 8.1$	$\Delta T = 10.0$
3	$\Delta T = 6.1$	$\Delta T = 9.3$	$\Delta T = 12.0$
5	$\Delta T = 7.9$	$\Delta T = 10.9$	$\Delta T = 15.0$
(b) *Copper plate with flange*			
0	$\Delta T = 3.2$	$\Delta T = 4.3$	$\Delta T = 4.9$
1	$\Delta T = 2.0$	$\Delta T = 2.0$	$\Delta T = 2.8$
2	$\Delta T = 2.4$	$\Delta T = 3.2$	$\Delta T = 5.2$
3	$\Delta T = 2.6$	$\Delta T = 3.6$	$\Delta T = 6.0$
5	$\Delta T = 4.0$	$\Delta T = 3.9$	$\Delta T = 7.5$

flow rate is considered to result from the larger cooling effect associated with a higher Q_j for the injected gas impinging on the wafer. This is evident by observing that the temperature at center of the wafer is lowest for each setting wafer temperature. The measured data for the copper plate with a flange indicated that the wafer temperature nonuniformity was reduced significantly by the addition of the radiation shield. For clear comparison the effects of the copper plates on $\Delta T_{\max}$ at different gas flow rates are demonstrated in Table 1. Note that the addition of the radiation shield is more effective at higher Q_j and T_{wf}. These results suggest that the high thermal conductivity of the copper and the addition of the radiation shield do result in better uniformity of the wafer temperature. It should be pointed out that the present method for temperature uniformity improvement is expected to be only slightly affected by the patterns on the wafer. Finally, it should be noted from Figs. 3 and 4 that during the ramp down process the wafer temperature is rather close to the copper plate temperature and the uniformity in the wafer temperature becomes even better.

It is of interest to compare the present results with those in the literature. For a 4-in wafer heated from the front and back sides by two banks of lamps, Gyurcsik et al. [20] found that the measured $\Delta T_{\max}$ is slightly above 15°C. With an annual guard ring, Load [3] noted that the $\Delta T_{\max}$ was as high as 30°C for a 4-in wafer. Through a better multizone lamp control $\Delta T_{\max}$ was reduced to about 12.5°C for a 6-in wafer by Moslehi et al. [21]. By using backside heating and a reflective showerhead, Hebb et al. [18] were able to reduce $\Delta T_{\max}$ to slightly below 10°C for an 8-in patterned wafer. Our measured $\Delta T_{\max}$, when compared with the above data from the literature [3,18,20,21], indicates that the method proposed in the present study to improve the wafer temperature uniformity is rather competitive.

3.2. Influences of showerheads on flow in processing chamber

In single-wafer rapid thermal processors, various showerheads are normally used to improve the gas flow distribution over the wafer. In the present study, two different showerheads for five different angles of gas injection, $\phi = 0°, 30°, 45°, 60°$ and $90°$, at the injection nozzles on the side wall of the mixing chamber were tested here. Fig. 5 shows the flow photos taken at steady state for an unheated wafer in the processor for different gas flow rates with the showerhead having 385 holes and gas injected radially ($\phi = 90°$) into the mixing chamber. The result in Fig. 5(a) indicates that for $Q_j =$ 4 SLPM the flow moving from the mixing chamber into the processing chamber is dominated by a weak distorted jet around the vertical axis of the processing chamber. Outside this jet the flow across the showerhead is rather weak. As the jet approaches the wafer, it becomes highly distorted. After hitting the wafer, it spreads somewhat irregularly over the wafer. At higher flow rates of 6 and 8 SLPM several jets form when the gas flow crosses the showerhead. These jets deform to a larger degree and occupy a larger space (Figs. 5(b) and (c)). Weak recirculations are seen outside the jets. It is noted that as the flow rate is raised to 12 SLPM, the flow entering the processing chamber is almost evenly distributed (Fig. 5(d)). However, weak flow recirculations still exist. When the gas is injected tangentially into the mixing chamber ($\phi = 0°$), the

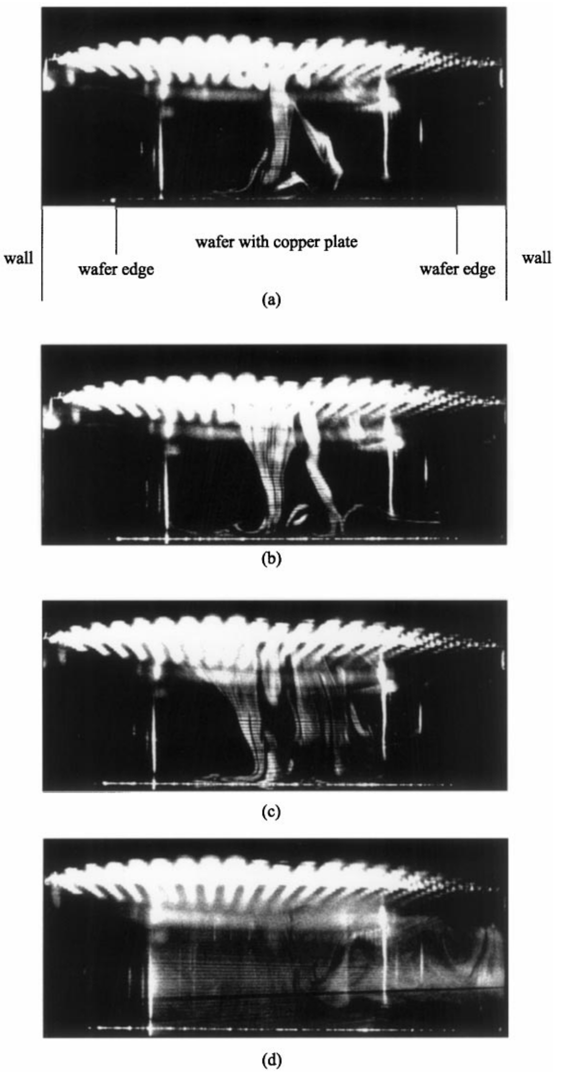

Fig. 5. Photographs of the flow pattern in the processing chamber with showerhead having 385 holes for $\phi = 90^\circ$ for (a) $Q_j = 4\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 18.6$), (b) $Q_j = 6\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 28.0$) and (c) $Q_j = 8\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 37.3$) and (d) $Q_j = 12\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 55.9$).

resulting gas flow is found to be mainly confined in the region near the side wall of the processing chamber. Hence, over the wafer the flow is rather nonuniform. For the injection angle between 0° and 90°, the resulting flow pattern is also between those discussed above for 0° and 90°.

When the showerhead contains a much larger number of 2401 smaller holes, the resulting flow in the processing chamber for $\phi = 90^\circ$ shown in Fig. 6 is no longer like jets. But flow recirculations form near the side wall of the chamber and the main flow is still restricted to the small zone around the axis of the chamber for $Q_j = 6\,\mathrm{SLPM}$ (Fig. 6(a)). Note that at a higher Q_j of 8 SLPM the recirculation is smaller and at $Q_j = 12\,\mathrm{SLPM}$ the recirculation is rather weak (Figs. 6(b) and (c)). Thus, at $Q_j = 12\,\mathrm{SLPM}$ the flow is nearly uniform as it moves vertically downwards. This suggests that a showerhead with rather small holes is needed to obtain a nearly uniform flow. It is interesting to note that more resistance is experienced as the flow crosses the showerhead containing small holes and hence the flow recirculates more intensely in the

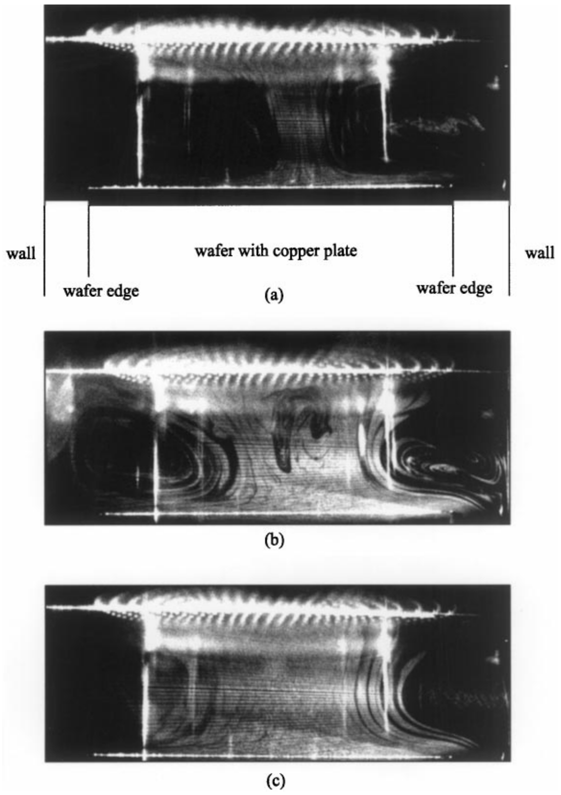

Fig. 6. Photographs of the flow pattern in the processing chamber with showerhead having 2401 holes for $\phi = 90^\circ$ for (a) $Q_j = 6\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 28.0$), (b) $Q_j = 8\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 37.3$) and (c) $Q_j = 12\,\mathrm{SLPM}$ ($\mathrm{Re_p} = 55.9$).

mixing chamber and lasts in a longer period of time. Thus, the downward flow across the showerhead is more uniform.

4. Concluding remarks

An experimental lamp heated, rapid thermal processor for processing a single silicon wafer was established here to investigate the flow in the processing chamber. A high thermal conductivity copper plate was placed beneath the wafer to improve the uniformity of the wafer temperature. Moreover, the use of showerhead to improve the flow distribution in the processor was examined. The major results can be briefly summarized in the following.

(1) The addition of a high thermal conductivity copper plate beneath the wafer can greatly improve the uniformity of the wafer temperature especially at the ramp-down process.
(2) A more uniform flow field can be obtained for the showerhead with small holes at certain inlet flow rate.

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