# A Novel Illuminator Design in a Rapid Thermal Processor

Min Hung Lee and Chee Wee Liu, *Senior Member, IEEE*

*Abstract*—The instantaneous insertion of an opaque shutter between the lamp arrays and the wafer in a rapid thermal processor can significantly increase the ramp-down rate from 90 to 400 °C/s during the cooling period. This shutter can prevent the residual heating of lamp filament as well as the self-heating from the reflector due to the mirror image of the wafer. To compensate for the weak irradiation intensity close to the edge of the linear lamps, a multiplane reflector design is used to increase the uniformity of irradiation intensity in the direction along the linear lamps. The distance between the reflector plane and the linear lamp is designed to be smaller at the edge, as compared to the center, of the linear lamp. Together with two oblique reflectors at the ends of the linear lamps, a typical three-plane reflector design can increase the uniformity by 60% in a typical lamp configuration.

*Index Terms*—Rapid thermal process, reflector, self-heating, spike ramp.

## I. INTRODUCTION

THE PROCESS technology of the ultrathin oxide and the ultrashallow junction in deep-submicrometer devices requires minimizing the thermal budget during the rapid thermal process (RTP) [1], [2]. Recently, the spike ramp became a highly considerable heating technology to reduce the heating cycle within one second [3]. This rapid ramp technology could heat the wafer over 1000 °C in several seconds. The typical ramp-up rate is from 50 °C/s to 400 °C/s [4] and is controlled by the lamp power and the reflector configuration to maintain the slip-free wafer. For the ramp-down cycle, gas flow conditions, chamber geometry, and physical characteristics of the wafer all have effects on the cooling stage. The unforced cooling ramp-down rate is 60 °C/s–80 °C/s [5], which is too slow, as compared to the ramp-up cycle. This slow ramp-down indeed prevents the effectiveness of the spike ramp process. The abrupt ramp-down of the cooling stage can achieve the ultrashallow junction formation after implant anneal, and thus prevents the short channel effect on deep-submicrometer devices [4], [6]. Although gas switching during the ramp-down cycle could be a solution, the thermal budget is still not minimized. It is desirable to increase the ramp-down rate to have an "impulse" temperature profile. In this work, we find that a shutter design can enhance the ramp-down rate. We analyzed the shutter performance by experiments and numerical simulation.

On the other hand, the rigid uniformity requirement is essential to have rapid thermal oxidation (RTO) and rapid
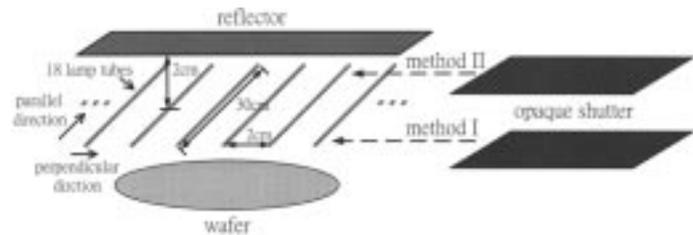
Fig. 1. A simplified schematic of the configuration of common RTP. In order to increase efficiency, a single planar reflector is commonly placed at one side of the lamp array to reflect the radiation to the wafer at the other side. In method I, a shutter is inserted instantaneously between the lamp array and the wafer right after the power-off. Both self-heating and residual filament heating can be suppressed in this method. In method II, the shutter is inserted between the lamp array and the reflector. Only the self-heating can be eliminated in this case.

thermal chemical vapor deposition (RTCVD) used in manufacturing fabs [7]. The illumination uniformity from lamp arrays is a prerequisite of temperature uniformity. Due to the different chamber configuration (quartz wall or stainless-steel wall), intense or weak irradiation of the wafer edge may be required. In any case, the reshaping of irradiation intensity from the lamps is necessary to increase the uniformity zone. We therefore use a multiplane reflector to reshape the irradiation intensity of a linear lamp array to extend the uniform irradiation zone along the linear lamp. Note that the uniformity irradiation zone may not yield the uniform temperature zone due to the edge effect of the wafer. For a quartz chamber, the gray body radiation (similar to the black body radiation, but the emissivity is less than unity) from the edge could lower the wafer edge temperature. For a stainless-steel chamber, the extra reflection from the chamber wall could increase the edge temperature of the wafer. Our method can also apply in both cases, if the details of the chamber are known.

## II. SHUTTER EFFECT ON THE SPIKE RAMP

Fig. 1 is a simplified schematic of the configuration in common RTP using a linear lamp array. The wafer temperature increases rapidly by the radiation of a high-power lamp. In order to increase efficiency, a single planar reflector is commonly placed at one side of the lamp array to reflect the radiation to the wafer at the other side. The residual heat of lamp filament and self-heating are two significant factors to maintain the wafer temperature after turning off the lamp power. During the ramp-down cycle, the hot filament in the linear lamps can not cool down immediately after the power is off, as shown in Fig. 2. For example, it takes about 6 seconds to drop the temperature from 2000 K to 1000 K in our stainless cold-wall
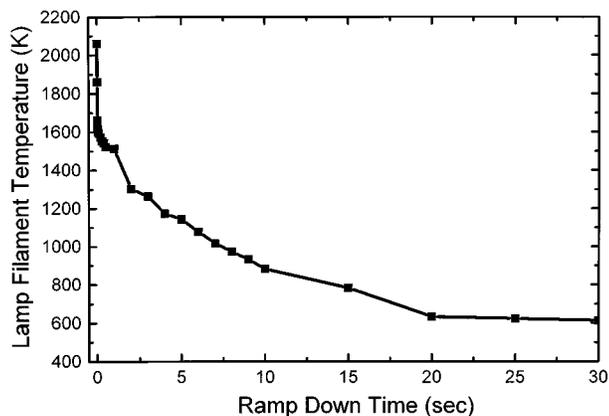
Fig. 2. The extracted ramp-down filament temperature as a function of ramp-down time.
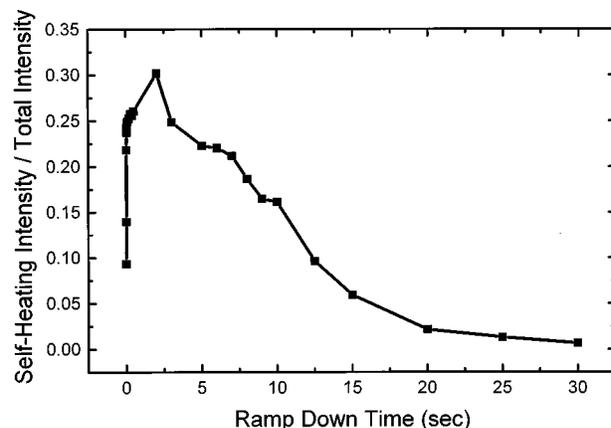


Fig. 3. The relative intensity of self-heating with respect to total irradiation on the wafer.

chamber. The residual heat will continue to heat up the wafers. The temperature profile is obtained by fitting the measured temperature profile with a heat conduction equation [8]

$$d \cdot \rho \cdot C_P \frac{\partial T}{\partial t} = -\varepsilon \sigma T^4 - h \cdot (T - T_{\text{gas}}) + K \cdot \nabla^2 T + Q \quad (1)$$

where

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|---|---|
| $\varepsilon, \rho, C_p$, and $K$ | emissivity, density, and specific heat and thermal conductivity of Si, respectively; |
| $d$ | thickness of the wafer; |
| $h$ | convection factor; |
| $\sigma$ | Stefan-Boltzmann constant $5.67 \times 10^{-12}$ W/cm$^2$ K$^4$; |
| $T_{\text{gas}}$ | gas temperature; |
| $Q$ | heating source with two components: the lamp filament irradiation (including the direct heating and the reflection from the reflector) and the reflector irradiation from the wafer itself (self-heating). |

The wafer irradiation reflected back to wafer itself by the reflector is called "self-heating." The models of these heating sources are based on [9]. During the ramp-down period, both sources are still effective. The residual heating from the filament is a black body radiation, depending on the filament temperature (Fig. 2). The relative intensity of self-heating with respect to total irradiation is given in Fig. 3. Due to its small thermal conductivity, the silicon wafer remains relatively hot after the power-off, and the self-heating of silicon wafer contributes more than 10% of the total power within in the initial 10 s. The self-heating component peaks up at 2 s and contributes 30% of the total power, since the filament temperature drops suddenly in this period.

To prevent these two sources from heating the wafer, we propose a shutter design in the illuminator. We also assume that the shutter is opaque with negligible reflectivity. In method I, a shutter is inserted instantaneously between the lamp array and the wafer right after the power-off. Both self-heating and residual filament heating can be suppressed in this method. In method II, the shutter is inserted between the lamp array and the reflector. Only the self-heating as well as the reflection of the filament can be eliminated in this case. The shutter could
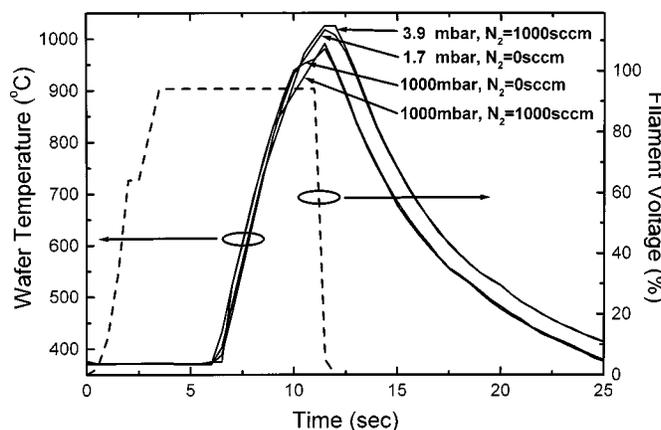


Fig. 4. The wafer temperature profiles measured by pyrometry with different pressure and N$_2$ flow conditions.

be implemented using the design of a camera shutter. We estimate the close time is on the order 10 ms for an 8-in technology processor if the close time is proportional to the shutter linear dimension [10].

To obtain the fitting parameters in (1), four different cooling conditions were performed under the same lamp power conditions. Fig. 4 gives the wafer temperature profiles measured by pyrometry with different conditions. The four conditions are high pressure without N$_2$ flow (pressure = 1000 mbar, N$_2$ flow rate = 0 sccm), high pressure with N$_2$ flow (pressure = 1000 mbar, N$_2$ flow rate = 1000 sccm), low pressure without N$_2$ flow (pressure = 1.7 mbar, N$_2$ flow rate = 0 sccm), and low pressure with N$_2$ flow (pressure = 3.9 mbar, N$_2$ flow rate = 1000 sccm). The convection effect due to the gas flow is not important in our reactor, since the 1000 sccm and 0 sccm N$_2$ flows yield a similar cooling profile. Note that, at low pressure without N$_2$ flow, convection effect is neglected in our simulation.

Fig. 5 gives the simulated temperature curves with the shutter insertion at low pressure without N$_2$ flow as well as the experimental data without shutter insertion. The solid line and dashed lines are the experimental data and simulation results, respectively. It takes 5.4 s from 1000 °C to 600 °C without shutter insertion. This value is reduced to be 1.6 s and 2.8 s for method I and method II, respectively. The initial ramp-down rate
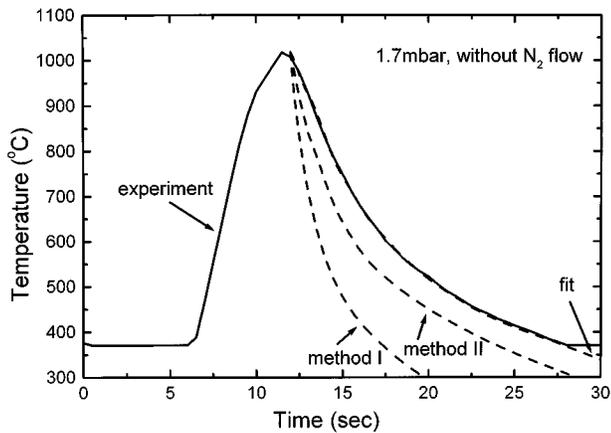
Fig. 5. The solid line and dash lines are experiment data and simulation results, respectively. The simulation parameters are obtained by fitting the experimental data under no shutter insertion, and the fitting reasonable well. The other two dash curve are the simulation for method I and method II.
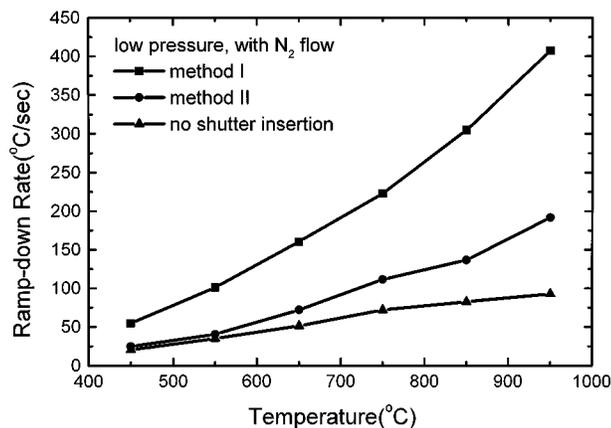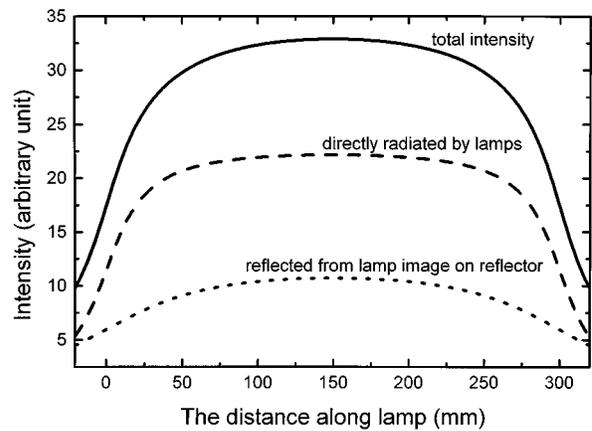


Fig. 7. The intensity distribution of a typical reflector design. The lamp tube length is 30 cm. The distance between the lamp array and the reflector is 2 cm. The wafer is 2 cm away from the lamp array.
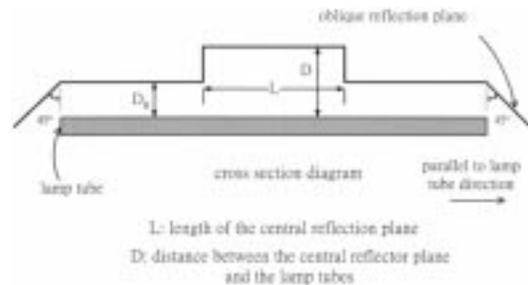


Fig. 6. The instantaneous ramp-down rate of no shutter insertion, method I and method II for low pressure with $N_2$ flow.



Fig. 8. A simplified schematic of the novel reflector design. The lamp tube length is 30 cm.

can reach as high as 400 °C/s and 200 °C/s for method I and method II, respectively, at the condition of low pressure with $N_2$ flow (Fig. 6). The results are significant because the cycle of ramp-down is usually within several seconds. The ramp-down rate is comparable with the ramp-up rate, and the annealing temperature profile becomes more symmetrical.

## III. NOVEL REFLECTOR DESIGN

In a cross-lamp configuration, there are two banks of linear tube lamps on each side of the wafer that are crossed mutually. The two-dimensional (2-D) control of the irradiation intensity on the wafer can be achieved by adjusting the individual lamp power of both banks. The proposed passive reflector design, which adds an extra control along the linear tube direction in the single-bank configuration, may not be very useful in the cross-lamp configuration. However, due to the consideration of the space and cost of the reactor, and the interference of pyrometry temperature measurement, the single-bank configuration is preferred in some applications. Note that the infrared from the lamp could be taken erroneously as the gray-body signal of the wafer during the pyrometry temperature measurement.

Linear lamps are conventionally used in RTP reactors. The arrangement of linear lamp tubes is shown in Fig. 1. The wafer in the reaction chamber was irradiated by infrared ray through the quartz window (not shown in figure). The array is composed of many linear lamp tubes, and its power can be controlled by the individual zone. Therefore, in the direction perpendicular to the lamp tubes, uniform irradiation distribution can be achieved by the multizone control of the lamp power.

However, in the parallel direction, the radiation intensity profile along the linear tube cannot be controlled, and the intensity of the lamp at both sides is weak (Fig. 7). In order to increase power, most commercial systems have a single planar reflector at one side of the lamp array to reflect the radiation to the wafer at the other side. The intensity distribution from the reflection is also shown in Fig. 7. The intensity distribution from the reflection is also weak at both sides (Fig. 7). In the processing of large-diameter wafers, the longer lamp tubes have to be used, because the uniform zone is much smaller than the tube length. This increases the cost and power consumption. We, therefore, designed a more effective reflector to solve this issue. Note that the calculation method used in this study can be found in [11].

In order to compensate for the weak intensity directly illuminated by lamp tubes at both sides, the reflector is designed such that the side plane is nearer to the lamp tubes than the central plane. Furthermore, a 45° oblique reflection plane is added in order to reflect the radiation at both ends of lamp tubes back to the wafer (Fig. 8). The reflector now is composed of three
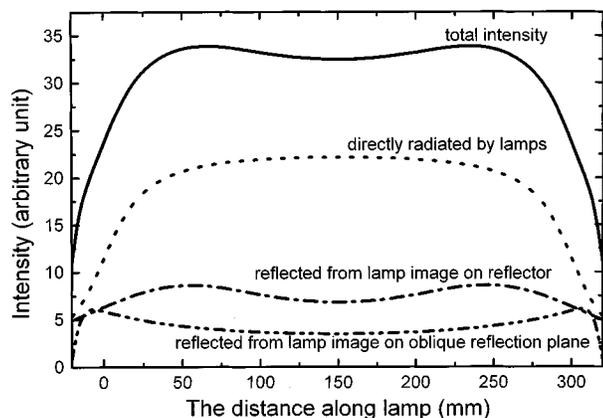
Fig. 9. The intensity distribution of the novel reflector design. The condition is $L = 13.5$ cm, $D = 6$ cm, $D_0 = 2$ cm, the distance between lamp array and wafer is 2 cm with 45 $^\circ$ oblique reflectors.
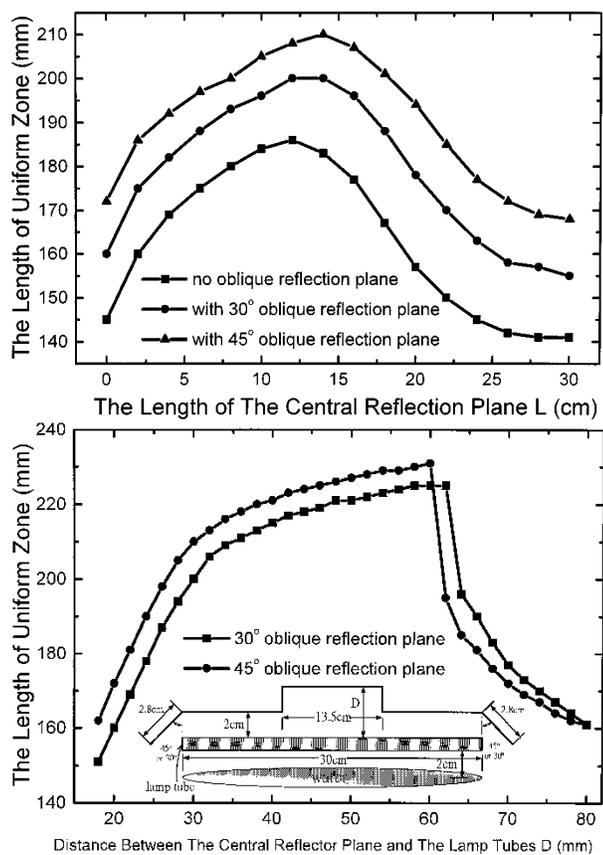


Fig. 10. (a) The length of uniform zone as a function of the length of the central reflection plane. The condition is $D = 3$ cm, $D_0 = 2$ cm and the distance between lamp array and wafer is 2 cm. The longest uniform zone is achieved for $L = 10$–15 cm. (b) The length of uniform zone as a function of the distance between the central reflector plane and the lamp tubes. The condition is $L = 13.5$ cm, $D_0 = 2$ cm, and the distance between the lamp and the wafer is 2 cm.

planes instead of a single plane. Because of the longer distance between the central part of the reflector and the lamp tubes, the radiation reflected at the central plane of the reflector is weaker, as compared to both side planes of the reflector. The 45° oblique reflection planes can also compensate the originally weak radiation at both ends to increase uniformity as in Fig. 9. This design

enhances the radiation at both sides and the length of the uniform zone increases.

To have the longest uniform zone, the length of the central reflection plane and its distance to the lamp tubes are crucial parameters. If we define the uniform zone to be the area within which the power difference is below 4% (approximately 1% difference in temperature according to black body irradiation), the influence of the central reflector length and the distance between the lamp tubes and the reflector plane are shown in Fig. 10(a) and (b), respectively. To obtain the best design of the central reflector length $L$ and the distance between the central reflector and lamp tubes $D$, we select constant $D = 3$ cm, and the maximum uniform zone is achieved when the central reflector length $L = 10$–15 cm, as shown in Fig. 10(a). Then, we select constant $L = 13.5$ cm, the optimum $D = 6$ cm is obtained for the maximum uniform length of 23 cm, as shown in Fig. 10(b). Although the mathematical optimum design has to be performed in 2-D domain consist of $L$ and $D$, this simplified procedure can achieve the increase of uniform zone by 60%, as compared to single plane reflector. Note, that the performance of the 30° oblique reflectors is also shown in Fig. 10(a), but it is inferior to the 45° oblique reflectors.

Actually, illumination uniformity of each lamp tube is not perfectly the same because of individual difference or time dependent change for instance. Since the proposed design is passive, i.e., the reflector can not be adapted during the process, the nonuniformity and degradation of the individual lamp lead to reduce the merits of this proposed design but it still have more advantage than the single flat reflector. However, this effect will not be serious as long as the uniformity and reliability of the lamp is greatly enhanced.

## IV. SUMMARY

To enhance ramp-down rate, we propose a shutter design in the illuminator. The shutter could be implemented using the camera shutter design and can be closed instantaneously after the power-off. Both self-heating and residual filament heating can be suppressed. The initial ramp-down rate can reach as high as 400 °C/s. Note that the original ramp-down rate is 90 °C/s (Fig. 6). Besides, a novel reflector is designed not only to increase lamp power efficiency, but also to improve the uniformity parallel to the linear lamp. The reflector has a variable distance between the lamp and reflector to compensate the nonuniformity of lamp irradiation along the linear lamp. Two oblique reflectors are also designed on the reflector edges to redirect the edge irradiation of lamp ends. The increase of 60% in irradiation uniformity can be achieved in a typical lamp configuration.

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**Chee Wee Liu** (M'99–SM'00) received the B.S. and M.S. degrees in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1985 and 1987, respectively, and the Ph.D. in electrical engineering from Princeton University, Princeton, NJ, in 1994.

In 1994–1996, he was an Associate Professor at National Chunghsin University, Taichun, Taiwan. Now he is an Associate Professor at National Taiwan University, Taipei, Taiwan. His current research interests include CMOS optoelectronics, optical interconnects, SiGe RF, and rapid thermal process. He invented the first MOS tunneling light-emitting diode and photodetector.

**Min Hung Lee** received the B.S. degree in physics from National Chunghsin University, Taichun, Taiwan, in 1996, and the M.S. degree in physics from National Taiwan University (NTU), Taipei, Taiwan, in 1998. He is currently pursuing the Ph.D. degree in the Department of Electrical Engineering, NTU.

His research interests include RTP equipment, RTCVD, and optical interconnects.