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Influence of the quartz window in a rapid thermal processing apparatus

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RTP (Rapid Thermal Processing) is widely used in manufacturing processes in high technology applications. In the present study, a 2D model of a RTP reactor is modified in order to investigate on the quartz window influence on the wafer temperature profile. The numerical calculations are performed in both transient and steady state, using the Monte-Carlo method for solving the radiative heat transfer equation. The absence of quartz window results in better temperature uniformity and in a shorter steady state reaching duration. The influence of the height of the wafer is also evaluated and optimised in steady state.

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1. Introduction

Rapid Thermal Processing (RTP) is widely used in manufacturing thin film processes for high technology applications [1,2]. The quality of the thin films strongly depends on the wafer temperature distribution [3,4]. The wafer temperature distribution has to be uniform in order to get homogeneous anneal. But the presence of strongly coupled phenomena induces temperature decrease towards the wafer edge [5,6]. Therefore, to improve the annealing quality, the involved phenomena causing the non-uniformity of wafer temperature have to be understood. For this purpose, computational fluid dynamics (CFD) is an interesting tool [7-9].

RTP reactors are single-wafer cold wall chambers where the wafer is rapidly heated up by halogen infrared lamps through a quartz window. In the present work, CFD simulations are carried out to study the influence of the quartz window on the wafer temperature distribution. A 2D model of a commercial RTP equipment developed by AnnealSys (Montpellier), the AS One 150 machine [10], is realized. The radiative heat transfer equation is solved by using the Monte Carlo method. First, the effects of the quartz window presence are investigated by analysing the simulation results performed in both transient and steady state. Secondly, the influence of the distance between the quartz window and the wafer is discussed by comparing the wafer temperature uniformity for different heating power. An optimisation of the wafer height and the heating power is proposed.

2. Experimental and modeling

Fig. 1 shows the 2D geometry of the AS One 150 machine. The wafer is heated by the radiative heat provided by a bank of eighteen tungsten infrared halogen lamps. The lamps are all supplied by the same amount of electrical power. The quartz window, between the wafer and the bank of lamps, ensures the reactor gas-tightness and lets the radiative energy heat the silicon substrate. The walls of the reactor are of stainless steel and their temperature is kept low by using cooling water. The pressure is maintained low by a pumping stage. A 150 mm diameter wafer is placed on quartz pins.

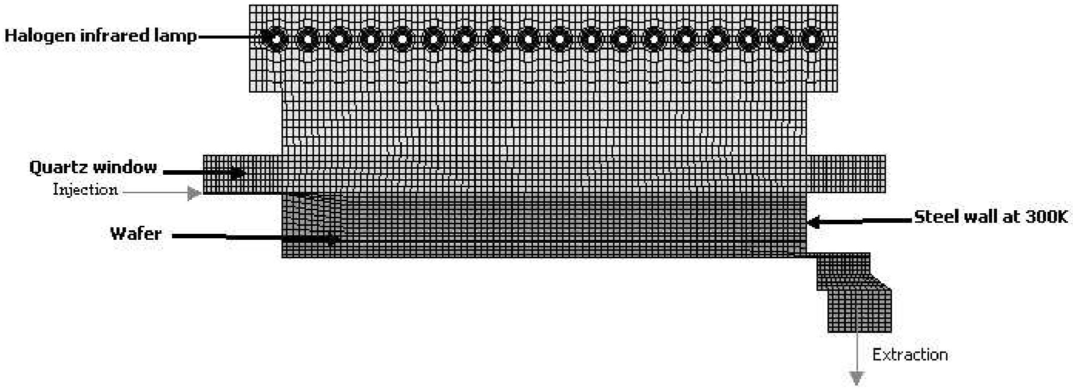


Fig. 1. The 2D AS One 150 machine geometry.

The numerical calculations of temperature and fluid flow are performed with a commercial computational fluid dynamics software CFD'ACE [11]. The finite volume method is used in the software code. The partial differential equations, which govern the mass and energy transport phenomena, are numerically integrated over each domain cell of the geometry [12,13]. The generalized form of the transport equation (generic conservation equation) is given by the below expression (1) which is composed of four terms that are respectively the transient term, the convective term, the diffusion term and the source term:

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla\cdot\left(\rho\vec{V}\phi\right)=\nabla\cdot(\Gamma\nabla\phi)+S_{\phi} \tag{1}$$

where ρ is the density, t is the time, ϕ is the general flow variable, $\vec{V}$ is the velocity and Γ is the diffusion coefficient.

To solve the radiative heat transfer equation, the Monte-Carlo method is used [14]. The principle of the method is to trace bundles of rays and to account for the various events (absorption, emission and scattering) occurring within each control volume. The tracing of the bundles requires to statistically randomise the sample of photons from their points of emission to their points of absorption [15].

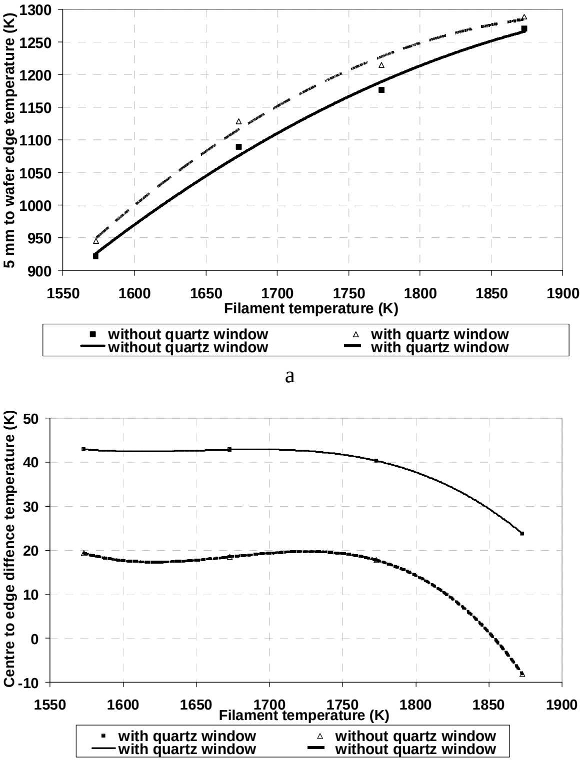
3. Results and discussion

3.1 Influence of the quartz window on the wafer temperature profile

In order to study the influence of the quartz window on the wafer temperature profile, two cases are analysed and compared. In the first case, the model described previously is considered with the quartz window. In the second one, the volume of the quartz window is replaced by nitrogen at the same low pressure as the whole reactor. In both the cases, simulations are realized in steady state and in transient state for different values of lamp filament temperature. The transient simulations are carried out using the implicit Euler method, which ensures unconditional numerical stability [16,17].

3.1.1 Steady-state study

When the quartz window is substituted by nitrogen, the wafer temperature is increased by about 20K at the centre and by about 50K at the edge. *Figure 2.a* presents the temperature at 5 mm from wafer edge in function of the lamp filament temperature with and without quartz window. Consequently, the difference of temperature between centre and edge, represented in *figure 2.b*, is about 22K lower without the presence of the quartz window.



a

b

Fig. 2. Wafer temperature in function of the filament temperature, a) 5 mm from edge temperature b) Centre to 5 mm from edge difference of temperature.

The wavelengths of the infrared radiative heat emitted by the filaments of the lamps go from 0.3 to 4 µm. The quartz window absorbs the radiative part between 2.6 and 2.9 µm and beyond 3.6 µm. When the quartz window is absent, all the radiative heat emitted by the lamps heats the wafer. Consequently, the obtained wafer temperature is higher.

Fig. 3 shows an example of quartz window temperature profile when the lamp filament temperature is fixed at 1673K. The corresponding wafer temperature profile is superposed.

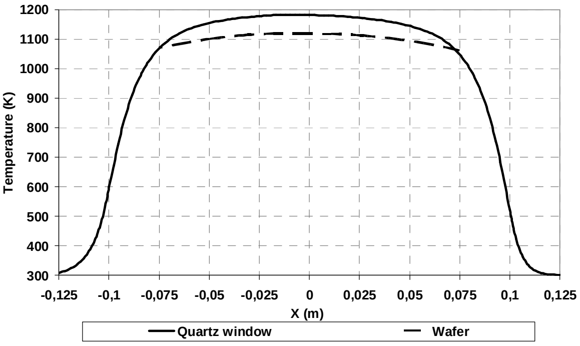


Fig. 3. Quartz window and wafer temperature profile for a filament temperature of 1673K.

As can be noticed in the example of Fig. 3, the temperature of the quartz window is maximal at the centre and decreases strongly towards its edges. The quartz window centre temperature is higher than the wafer's. The low temperature at the edge of the quartz window can be correlated to the wafer edge temperature decrease. So, the uniformity of the wafer temperature can be improved if the quartz window profile is flatter. In order to do so, double quartz window cooled with oil or water have been proposed by some RTP apparatus manufacturers [18,19]. The remaining but smaller difference when there is no quartz window shown in Fig. 2.b is due to the influence of the cooled stainless steel wall of the reactor.

3.1.2 Transient-state study

The evolution of the wafer temperature is obtained in the simulations for two heating power, a low one and a high one. A filament temperature of 1473 K is chosen for the low heating power and 1773 K for the high one. Fig. 4 shows the evolution of the wafer centre temperature for the high heating power with and without quartz window. Similar results are obtained for the low heating power.

The wafer temperature increases and stabilizes in all the cases. Moreover, we can observe that in transient state heating, the centre to edge difference of temperature is less important than when the steady state is reached. Fig. 4 indicates that when the quartz window is present, the duration to reach steady state is about 2500s. But, when the quartz window is replaced by nitrogen, this duration is only of 250s. For the low heating power, the latter duration is 400s whereas it is 3500s when the quartz window is present.

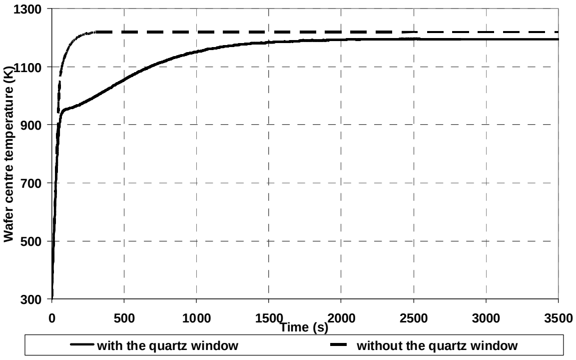


Fig. 4. Evolution of the wafer centre temperature for a high power applied (filament temperature of 1773 K).

The evolution of the quartz window centre temperature can be observed in Fig. 5 for the high filament temperature of 1773 K. It is similar to the wafer temperature one.

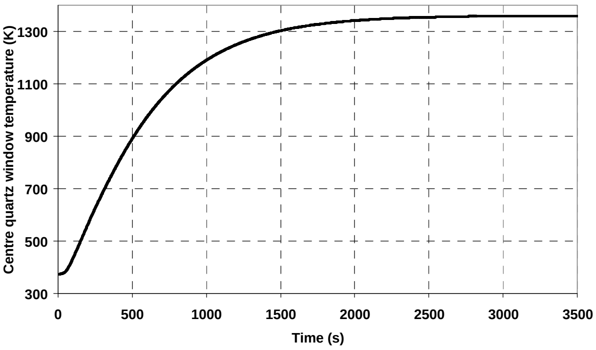


Fig. 5. Evolution of the quartz window centre temperature for a high power applied (filament temperature of 1773 K).

3.2. Influence of the wafer height

The influence of the distance between the quartz window and the wafer on the wafer temperature profile is evaluated in steady state. In order to vary this distance, the wafer height is modified by changing the size of the quartz pins holding the wafer. The temperatures are taken at the centre and at 5 mm from the edge of the wafer for three wafer heights going from the standard position of 0.006 m to 0.020 m. The temperatures of the lamp filaments are varied in order to establish a relationship between the heating of the lamp, the wafer-quartz window distance and the wafer temperature. Finally, both the lamp filament temperature and the wafer height are optimised by minimising the difference between the centre and the 5 mm from edge temperature for a given wafer centre temperature.

3.2.1. Relations

Fig. 6 shows the wafer centre temperature T(x = 0 m) determined from simulations for the three wafer heights at different lamp filament temperatures.

The wafer centre temperature *T(x=0m)* can be expressed as a function of the height *h* and the lamp filament temperature T_{fil} :

$$T(x=0\ m) = (-33.105h + 1.5098)\ T_{fil} + 60469h - 1447 \quad (2)$$

Analogue plots are obtained for the temperature at 5 mm from the wafer edge and lead to the following expression for *T(x = -0.070 m)*:

$$T(x=-0.070\ m) = (-25.799h + 1.4059)\ T_{fil} + 48976h - 1317 \quad (3)$$

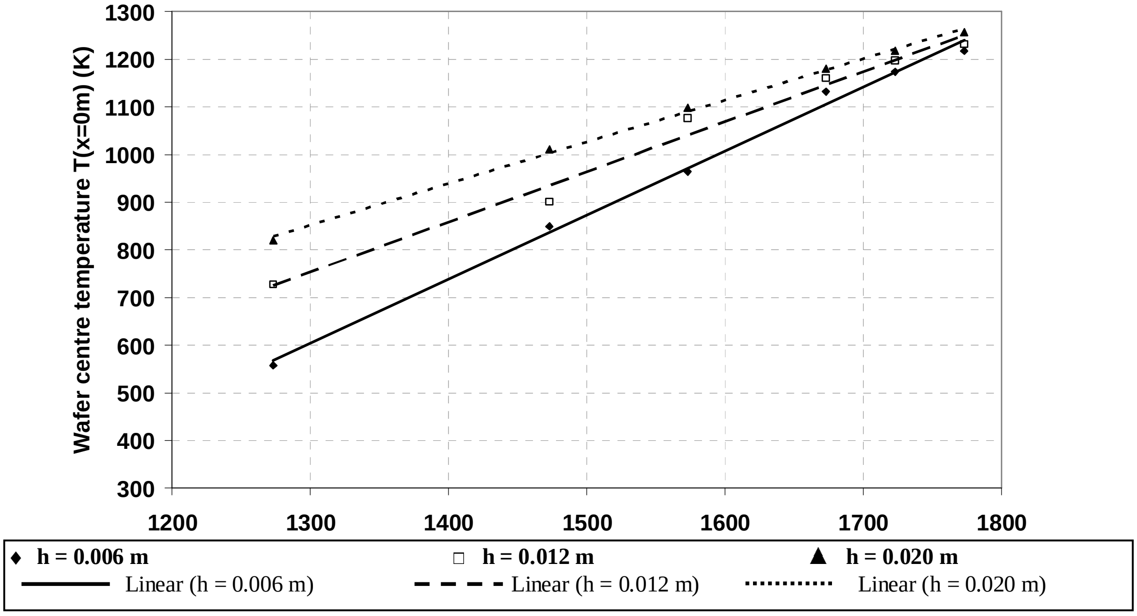


Fig. 6. Wafer centre temperature for different filament lamp temperatures and for the three heights of the wafer.

3.2.2. Optimisation

In order to optimise the RTP apparatus, the difference between the two functions (2) and (3) has to be minimised for a chosen wafer centre temperature. The Fig. 7 graph gives both the height (—) and the filament temperature (--) that provide the best uniformity versus the chosen wafer centre temperature ranging from 700 to 1300 K.

For example, to obtain a wafer centre temperature of 1200 K, the Fig. 7 graph indicates both a height of 0.020 m and a filament temperature of 1700 K. In this case, the temperature difference between centre and edge is of 28 K, in other words 2.3% of the wafer centre temperature. As mentioned above, in the transient state, the centre to edge difference of temperature is less important than when the steady state is reached. So, a better uniformity of temperature can be expected in RTP processes where the heating duration is shorter the steady state reaching duration.

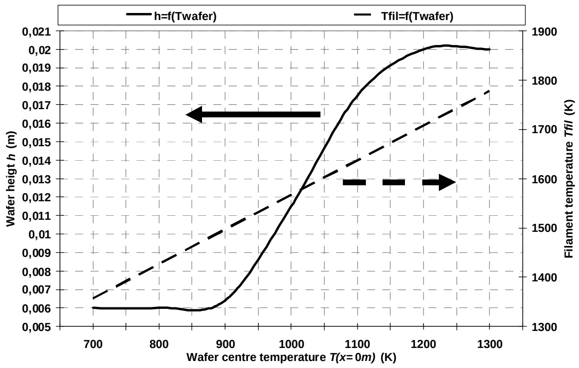


Fig. 7. Optimised height and lamp filament temperature for the chosen wafer centre temperature.

To obtain a low wafer temperature (700 to 900 K), the wafer should be kept far from the quartz window. On the other hand, to have a uniform high wafer temperature (1150 to 1300 K), the wafer has to be close to the quartz window and the power lamp should be increased. The quartz window at a high temperature influences the wafer temperature in the right way. Finally, to get wafer temperatures in between, the height and the filament temperature must have intermediate values.

4. Conclusions

In the present study, the influence of the quartz window on the wafer temperature profile in the RTP process is better understood through 2D simulations.

The substitution of the quartz window by nitrogen leads to the increase of the wafer temperature difference between its centre and edge with the presence of the quartz window in steady state. It also puts into evidence that the wafer temperature profile can be correlated to the quartz window one. The transient simulations reveal that the presence of the quartz window increases the duration of steady state reaching.

The relations between the wafer temperature and both the wafer height and the filament temperature in steady state are obtained. They lead to the optimisation of the wafer temperature uniformity by adjusting the wafer height and the lamp supplied power. A better temperature uniformity is realized in the standard position for low wafer temperatures and in a position close to the quartz window for high wafer ones.

As the usual duration of Rapid Thermal Processes is shorter than the steady state reaching one, further work is in progress in order to optimise the wafer temperature uniformity in transient state. First simulation results reveal that the centre to edge difference of temperature is less important than that when the steady state is reached.

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