IMPROVEMENT OF TEMPERATURE UNIFORMITY IN RAPID THERMAL PROCESSING SYSTEMS USING MULTIVARIABLE CONTROL[1]

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ABSTRACT

During rapid thermal processing (RTP) of a semiconductor wafer, maintenance of near-uniform wafer temperature distribution is necessary. This paper addresses the problem of insuring temperature uniformity in a cylindrical RTP system with multiple concentric circular lamps.

A numerical technique is presented for optimizing steady-state temperature distribution by independently varying the power radiated by each lamp. It is shown for a simulated system, over a wide range of temperature setpoints, that the temperature uniformity achievable with multivariable ("multiple knob") control of lamp powers is significantly better than that achievable with scalar ("single knob") control.

The difficulties of using scalar control in RTP are more severe in the case of temperature trajectory design than in the case of steady-state temperature maintenance. For example, with scalar control the rate of temperature increase during ramping is limited because temperature nonuniformity can cause slip defects in the wafer. A numerical technique is presented for designing multivariable lamp power trajectories to obtain near-optimal temperature uniformity while wafer temperature tracks a specified ramp, resulting in slip-free ramp rates much faster than those achievable with scalar control.

EQUIPMENT MODEL

The results in this paper have come from computer simulations based on a mathematical model of the idealized RTP system shown in Figure 1. The wafer is suspended on three quartz pins; the effects of the pins on heat transfer is neglected. The wafer diameter is six inches; approximate lamp and chamber dimensions can be inferred from Figure 1, which is to scale.

A thermal model for this system was developed using the approach of Lord [1]. The surfaces of the inner surface of the chamber and of the wafer are modeled as gray, diffuse, opaque surfaces having emissivities of 0.6, with the exception of special zones in the chamber ceiling. These special zones are four lamps, modeled as concentric, flat, black-body surfaces with the center lamp circular and the other three annular. It is assumed that the power radiated by each lamp can be directly commanded by the RTP system's controller. The remainder of the chamber inner surface is taken to have a temperature of 27°C. After dividing the wafer and chamber surfaces into zones, radiation heat transfer in the system can be computed using angle factors, as described in [2].

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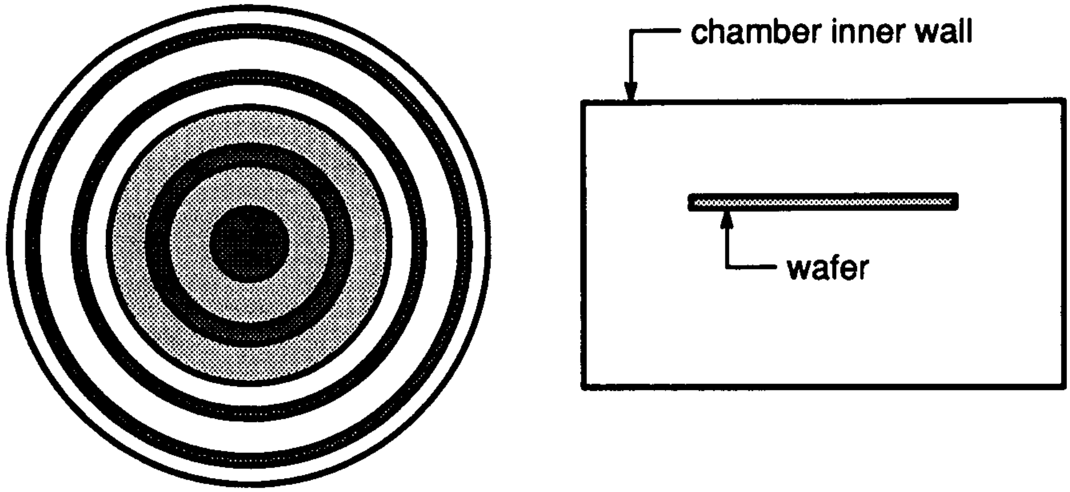

Figure 1: *Equipment model. Top view on left shows chamber inner wall (outermost ring), lamps (dark gray), and wafer (light gray). Cross-section is on right.*

The wafer is characterized as a thin disk of pure silicon. The wafer thermal model is developed in a cylindrical coordinate system. Temperature is assumed to be constant in the axial or z-direction because the wafer is very thin; temperature is assumed to be independent of the azimuthal angle θ due to symmetry. Consequently, temperature is dependent only on radial position r and time t. The wafer is modeled as a collection of twenty concentric annular elements. For each element i we can write a differential equation for its temperature T_i:

$$\dot{T}_i = \frac{1}{m_i C_p(T_i)} \left\{ f_i(T_1, \ldots, T_{20}) + \epsilon \sum_{j=1}^{4} F_{ij} P_j \right\}, \tag{1}$$

where P_j is the total power radiated by lamp j, ϵ is the emissivity, and where for element i, m_i is the mass, $C_p(T_i)$ is the (temperature-dependent) specific heat, f_i is heat transfer from all twenty wafer elements, and F_{ij} is the effective angle factor from lamp j to element i. The function f_i includes the effects of heat conduction in the wafer, convective heat loss from the wafer, and radiative heat transfer between the wafer and the chamber walls.

Steady-state wafer temperature distribution can be found numerically by setting $\dot{T}_i = 0$ in (1) and using Newton's method on the resulting system of nonlinear equations. Dynamic temperature trajectories can be obtained numerically with an ordinary differential equation solver.

While some of the assumptions made in the formulation of this model are unrealistic, the behavior of the model captures qualitatively the actual behavior of an RTP system well enough that the model can be used to make some important observations about RTP system design and control.

Method for optimizing steady-state temperature distribution

Here we consider the problem of choosing lamp power setpoints that result in the steady-state temperature at each point on the wafer being close to some specified temperature T_s. A reasonable goal is to choose lamp settings that minimize the worst-case difference

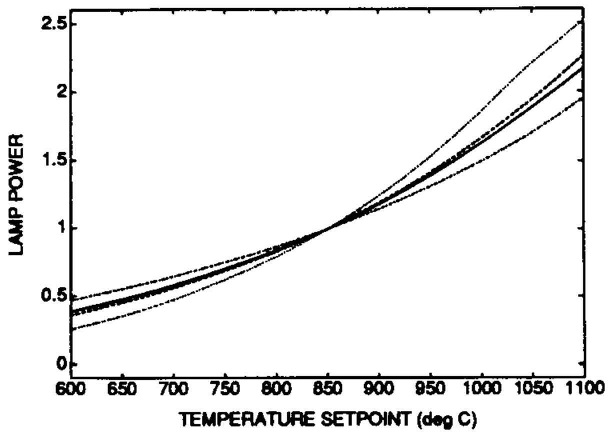

Figure 2: *Optimal lamp vectors for steady-state temperature hold, relative to optimal lamp vector for* 850°C. *From innermost to outermost lamp, corresponding curves are solid, dashed, dotted, dash-dot.*

between wafer temperature and T_s, that is minimize the quantity

$$\max_i |T_i^{ss}(P) - T_s|, \tag{2}$$

where T_i^{ss} is the steady-state temperature of element i, and $P = [\ P_1 \ \ P_2 \ \ P_3 \ \ P_4\ ]^T$. Finding the P_j's to minimize (2) is done as follows:

1. Set $\dot{T}_i = 0$ and $T_i = T_s$ in (1) and find an approximate solution $\hat{P}(T_s)$ to the resulting overdetermined linear algebraic equation in P.

2. Find the optimal lamp vector $P^{\text{opt}}(T_s)$ by linearizing the problem about the steady-state temperature distribution corresponding to $\hat{P}(T_s)$.

Each of the above two steps involves a very small linear programming problem that can be solved in a few seconds by a workstation or PC. The physical constraint that all the entries of $\hat{P}(T_s)$ and $P^{\text{opt}}(T_s)$ must be positive is explicitly observed.

Unfortunately, space limitations prevent detailed comparison of this method of achieving near-uniform steady-state temperature with that in [3]. Briefly speaking, the method of [3] involves approximating temperature as a quadratic function of wafer illumination flux density and approximately optimizing uniformity by minimizing mean square error between desired and actual wafer illumination, while the method proposed here makes no such approximations and optimizes (2) directly.

Optimal steady-state temperature distribution for simulated system

The lamp power settings that minimize the worst-case difference between wafer temperature and T_s for values of T_s between 600°C and 1100°C are plotted in Figure 2. These lamp power values are plotted relative to the optimal lamp settings for 850°C, which are, from innermost to outermost lamp, 0.35kW, 1.61kW, 1.35kW, and 10.0kW. The largest deviation between setpoint and actual temperature is 0.39°C, which occurs when T_s is 1100°C. It is important to note that as temperature changes, the ratios between individual lamp settings change significantly. A consequence is that if there is scalar control of the lamp power — if one knob simultaneously controls all four lamps — temperature variation may be significantly greater than necessary at some setpoints. This is illustrated in

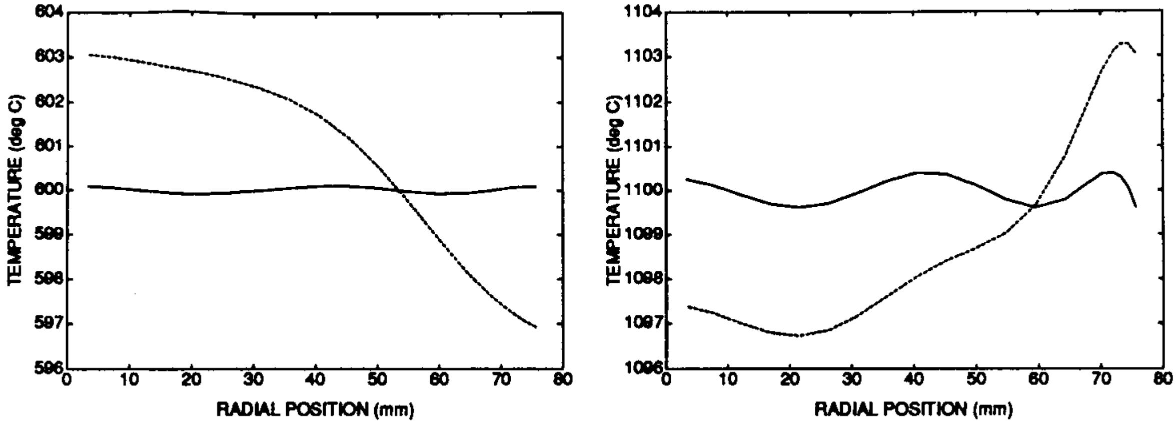

Figure 3: *Steady-state temperature distributions with setpoints of* 600°C *and* 1100°C. *Solid curves: steady-state optimal lamp vector. Dashed curves: lamp vector scaled from optimal lamp vector for* 850°C.

Figure 3 which shows the optimal temperature distributions at 600°C and 1100°C along with temperature distributions resulting from scaling the optimal lamp vector for 850°C. In each case multivariable control results in a worst-case temperature deviation of less than 0.4°C while with scalar control the worst-case temperature deviation is about 3°C.

EXPERIMENTAL RESULTS FOR STEADY-STATE TEMPERATURE HOLD

Experiments have been conducted with an RTP system with three independently-controlled rings of halogen lamps and three thermocouple temperature sensors welded to a four-inch-diameter test wafer. The thermocouples are located at the wafer center, near the edge, and halfway in between.

By means of simple hand adjustment of lamp settings it has been possible to get *all three steady-state thermocouple readings within* 2°C *of temperature setpoints* between 600°C and 800°C in vacuum and between 500°C and 800°C with nitrogen in the chamber at 1 Atm.

Processing experiments [4] confirm that steady-state temperature uniformity using these hand-tuned lamp settings is very good. These experiments show that the wafer temperature profile is indeed circularly symmetric and that the temperature variation at radii in between the thermocouple radii is small.

METHOD FOR NEAR-OPTIMAL TRAJECTORY DESIGN

Here we consider the problem of having wafer temperature track a specified trajectory. We would like each T_i to be close to a specified temperature $T^{\mathrm{spec}}(t)$ for all times t between start time t_0 and end time t_1, assuming that for each i, $T_i(t_0)$ is very close to $T^{\mathrm{spec}}(t_0)$.

One way to achieve the above goal is to choose, for each t between t_0 and t_1, the lamp vector $P(t)$ to be the sum of two vectors:

- $P^{\mathrm{opt}}(T^{\mathrm{spec}}(t))$, the optimal lamp vector for steady-state hold at $T^{\mathrm{spec}}(t)$, and
- $\dot{T}^{\mathrm{spec}}(t)C_p(T^{\mathrm{spec}}(t))P^{\mathrm{unif}}$, where P^{unif} is an approximate solution to the overdeter-

mined linear algebraic equation in P given by

$$\frac{\epsilon}{m_i}\sum_{j=1}^{4} F_{ij}P_j = 1\frac{\mathrm{W}}{\mathrm{kg}} \tag{3}$$

for $i = 1, \ldots, 20$.

The vector $P^{\mathrm{opt}}(T^{\mathrm{spec}}(t))$ compensates for loss of heat from the wafer by radiation and convection, while the vector $\dot{T}^{\mathrm{spec}}(t)C_p(T^{\mathrm{spec}}(t))P^{\mathrm{unif}}$ adds enough additional heat to obtain a rate of temperature increase of close to $\dot{T}^{\mathrm{spec}}(t)$ at all points on the wafer. Finding P^{unif} involves the solution of a linear programming problem similar to those solved to find optimal steady-state lamp vectors.

Near-optimal trajectory design for simulated system

Figure 4 shows a temperature trajectory which takes the wafer from 600°C to 1100°C in ten seconds along with the lamp power trajectory designed to achieve this temperature trajectory. Note that independent control of lamp powers is essential for obtaining this lamp power trajectory. The initial condition is taken to be 600°C across the wafer. The largest deviation from the specified trajectory at any time and at any point on the wafer is 2.3°C, and the largest difference in temperature between any two points on the wafer at any one time is 2.6°C.

If we start with the same initial condition but simply set the lamp vector to the steady-state optimal value for 1100°C and wait for the system to settle, we find that it takes over 12 seconds for all points on the wafer to get within 5°C of 1100°C, as shown in the left-hand plot of Figure 5, and that at times differences in temperature between points on the wafer exceed 18°C, with the wafer edge is at times considerably hotter than the wafer center, as shown in the right-hand plot. Having the wafer edge substantially hotter than the center during ramp-up to a near-uniform steady-state is a common problem in RTP, noted for example in [1, 5, 6, 7, 8].

Figure 6 shows worst-case temperature difference across the wafer plotted against time for the near-optimal multivariable lamp power trajectory and for the step-to-final-setting lamp power trajectory.

Approximate thermal stress computations following the approach of [9] show that with the carefully designed lamp power trajectory, the ratio of thermal stress in the wafer to yield stress peaks at about 0.16, while when the lamp power is immediately set to its final value, this ratio at times exceeds 1.2. By turning up the power slowly instead of instantly, it is likely that slip-free ramp-up can be achieved with a fixed-ratio control scheme, but this would further lengthen ramp-up time.

Conclusions

It has been shown that for a simulated RTP system with an array of concentric circular lamps, independent control of lamp powers allows

- much better wafer temperature uniformity during steady-state hold and ramp-up and
- faster slip-free ramp-up

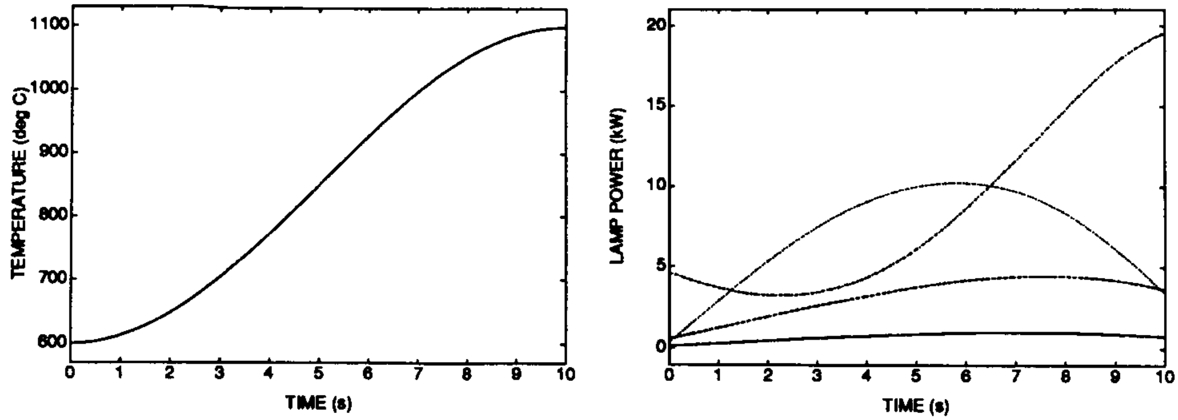

Figure 4: *A temperature trajectory and a lamp power trajectory designed to approximately achieve it. From innermost to outermost lamp, curves corresponding to lamp powers are solid, dashed, dotted, dash-dot.*

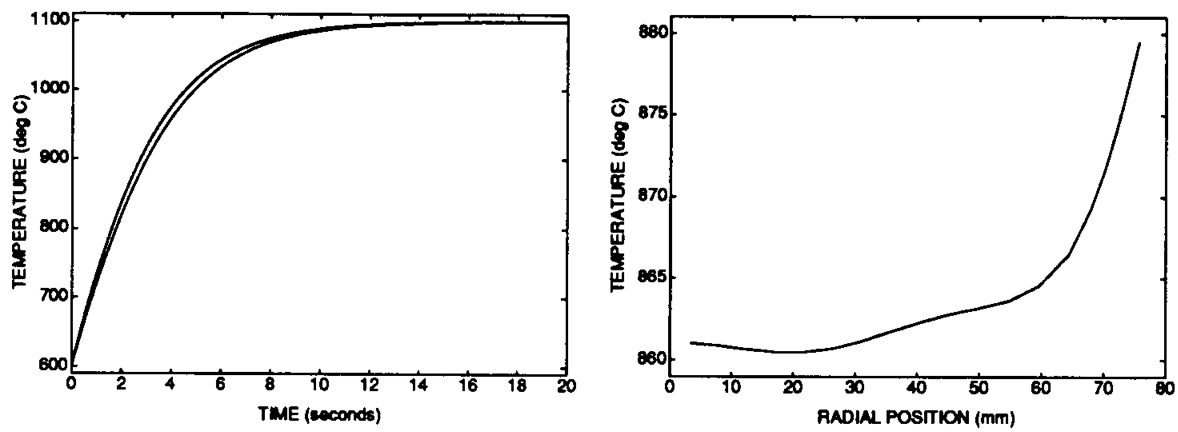

Figure 5: Left: *Minimum and maximum wafer temperatures against time when lamp power is abruptly switched to optimal lamp power for steady-state hold at* 1100°C. Right: *Wafer temperature profile about* 2.5 *seconds after lamp power is switched.*

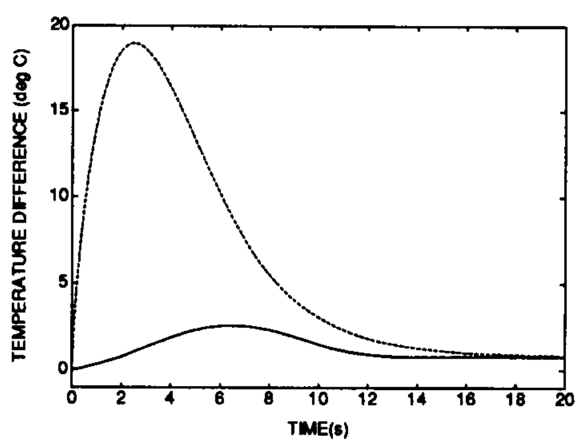

Figure 6: *Largest difference in temperature between any two points on the wafer plotted against time for near-optimal multivariable lamp power trajectory (solid) and step-to-final-setting lamp power trajectory (dashed).*

than does control based on a fixed ratio of lamp powers. For the simulated system the constraint of fixed lamp power ratio perhaps seems artificial, but for real RTP systems with lamp arrays driven by a single power supply or with a single lamp and carefully tuned reflectors or guard rings an equivalent constraint arises quite naturally.

For real RTP systems, models will be imperfect, some model parameters will be uncertain, and disturbances will be present. The techniques presented here for optimization of steady-state temperature uniformity and near-optimization of temperature uniformity during transients are partly based on knowledge of a perfect model for a disturbance-free RTP system; consequently, direct application of these techniques to real systems is not practical. But these techniques are valid for determining *limits of performance* for real systems with feedback control of temperature. Roughly speaking, it is very unlikely that optimal closed-loop, imperfect-model performance will be any better than optimal open-loop, perfect-model performance. So closing the loop cannot alleviate the uniformity problems associated with scalar control. Thus this paper supports a statement made in [10]: that a multiple lamp system with multisensor active control may be required to insure steady-state and transient uniformity.

A much more comprehensive discussion of the ideas in this paper and a description of a technique for *exact* optimization of transient temperature uniformity will appear in [11].

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