DESIGN OF RAPID THERMAL PROCESSING SYSTEM BASED ON MSC/NASTRAN THERMAL ANALYSIS

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Abstract

This paper describes a finite element model of rapid thermal processing (RTP) system for semiconductor manufacturing and its implementation with MSC/NASTRAN. The model is used for optimization of geometry and configuration of heating lamps in the RTP system. MSC/NASTRAN serves two main purposes: (1) calculation of parameters for design optimization algorithm using VIEW module; (2) performance evaluation of obtained configuration using heat transfer analysis. Condition of achievability of temperature uniformity is used as the goal of design in an interactive procedure with MSC/NASTRAN program in the kernel. Version 68 allows to improve the design procedure. Possible further refinements are discussed.

1 Introduction

During the manufacture of integrated circuits (ICs), silicon wafers undergo a number of processing steps typically at high temperatures; much of this processing takes place in a rapid thermal processing (RTP) chamber, where high levels of light power, emanating from tungsten-halogen heating lamps mounted so as to view the wafer directly, are applied to the wafer, eventually raising its temperature to high values. Usually, the wafer is kept at high temperature a few minutes and then it is allowed to cool down. Some reviews of state of the art RTP systems, as well as their use in semiconductor manufacturing, are given in [1], [2], and [3].

The method described in this work provides a simple and efficient procedure of design, based on a hierarchy of models and algorithms of an RTP system [5]. The components of this method include: a model of heat transfer of a silicon wafer with wavelength dependent emissivity; a detailed finite element model, incorporating specific physical and geometrical properties of an RTP system; a simplified partial differential equation for heat control in the RTP involving lamp ring radiation functions; a method of calculation of lamp ring radiation functions, using the finite element model of the RTP system; a simple graphical criterion of achievability of temperature uniformity by a given configuration of an the RTP system; and a formula for optimal control in the form of a constant vector multiplied by a scalar function, depending on the reference temperature trajectory.

Derivation and discussion of these components was presented elsewhere [5]. In this paper we concentrate in presenting the finite element model of the RTP system and using MSC/NASTRAN in design procedure.

2 Implementation of the Finite Element Model of an RTP System on MSC/NASTRAN

As was discussed in [5], finite element model of an RTP system serves two purposes: 1) to calculate the parameters of the simplified partial differential equation for heat control and 2) to estimate the quality of the design by applying the final designed configuration of the lamps and the corresponding control to the model.

Using the finite element method, an RTP system is represented by a large number of 3-dimensional, 2-dimensional and boundary elements [6]. Each element has several grid points where temperature and other parameters (e.g., stress) are calculated. The heat exchange between the elements can be described by the following system of equations [6]:

$$\mathbf{K}\mathbf{T} + \mathbf{C}\dot{\mathbf{T}} = -\mathbf{A}\left[\mathbf{I} - \mathbf{E}_\alpha \mathbf{D})\right] \cdot \sigma \mathbf{E}_\epsilon \mathbf{T}^4 \tag{1}$$

where: $\mathbf{T}$ is a vector of temperatures at the elements; $\dot{\mathbf{T}}$ is a vector of temperature gradients (in time); $\mathbf{K}$ is a symmetric matrix of heat conduction coefficients; $\mathbf{C}$ is a symmetric matrix of heat capacity coefficients;

$$\mathbf{D} = [\mathbf{A} - \mathbf{F}(\mathbf{I} - \mathbf{E}_\alpha)]^{-1}\mathbf{F}; \qquad (2)$$

$\mathbf{E}_\epsilon$ and $\mathbf{E}_\alpha$ are diagonal matrices of (temperature dependent) emissivities and absorptivities of the elements; σ is the Stefan-Boltzman constant; **A** is a diagonal matrix of areas for boundary elements (and zeros for the others elements); and **F** is a symmetric matrix of radiation exchange coefficients. Exchange coefficients can be efficiently calculated for difficult geometries by using VIEW module of MSC/ NASTRAN. They may be adjusted to include in the calculation some additional effects (e.g. semi-transparence of the quartz window) [7].

The quality of the design may be investigated by the application of the resulting configuration of the lamps and the corresponding control to the finite element model of the RTP system. Our model consists of four major components: the silicon wafer, the quartz window, the RTP chamber, and the tungsten-halogen heating lamps. The model geometry is illustrated in Fig. 1. The spatial arrangement of the three circular lamp zones as well as other aspects of the geometry should be chosen to achieve the objectives of the design.

The two-dimensional finite elements supported by MSC/NASTRAN include triangular element and quadrilateral element (in version 68 the are described by CHBDYE or CHBDYG). Two types of three-dimensional finite elements – pentahedron (CPENTA) and hexadedron (CHEXA) are used in our finite element model. The sizes and shapes of these elements are flexible, but accuracy may be reduced if triangular sides of pentahedron or opposite sides of hexahedron are not parallel within 30° [8].

For the purpose of heat transfer analysis four major components of the RTP station were subdivided into finite elements as follows:

1. The silicon wafer (6 inches in diameter) was subdivided into 132 finite elements, which can be grouped into $N = 11$ circular zones and 12 sectors (12 CPENTA and 120 CHEXA elements , with 132 correspondent boundary elements (CHBDY) on the top surface and 132 –on the bottom surface. Due to the fact that the central ring of halogen lams is usually positioned most closely to the wafer surface, the temperature gradients in the central part of the wafer were expected to be higher. Accordingly, the central part of the wafer was subdivided into 12 relatively small PENTA elements. The remaining part of the wafer was subdivided into 10 circular zones consisting of 12 HEXA elements each, with dimensions of HEXA elements increasing toward the edge of the wafer. The thickness of all the elements comprising the FE model of the wafer was taken to be 0.025″.

2. The quartz window on the top of RTP chamber was subdivided into 10 PENTA elements, each having a common point at the center of the window. The thickness of all PENTA elements was taken to be 0.5″.

3. The RTP chamber was subdivided into 30 two-dimensional elements. The vertical walls of the chamber were divided into 10 boundary CHBDYG ele-

ments of equal size with TYPE=AREA4. The bottom part of the chamber was divided into 20 CHBDYG elements: ten with TYPE=AREA3 and ten with TYPE=AREA4. The ten triangular elements comprise the inner disk on the bottom of the chamber and allow to simulate the sapphire window serving for remote temperature measurement by radiation thermometers located outside the RTP chamber.

4. The tungsten-halogen lamps were modeled as POINT elements grouped into three rings with one, twelve, and twenty four lamps respectively. The diameter of the inner lamp was taken to be 1″, all other lamps have the diameter of 0.7″. This model allows us to move outer and middle rings of the lamps fixing the inner lamp under the center of the wafer.

3 Using MSC/NASTRAN in Calculation of Lamp Ring Radiation Functions

A detailed finite element model of an RTP system may be used to perform simulation experiments with different geometrical configurations and algorithmic control of the heating lamps. However it is difficult to directly apply analytical methods of optimization to the model, because of its large dimension and lack of simplifying features.

A simple partial differential equation (PDE) for the heat transfer of a thin silicon wafer in an axi-symmetrical RTP system is given by the following equations [5]:

$$\begin{aligned}\rho c(T(\cdot,t))\tfrac{\partial T(r,t)}{\partial t} &= k(T(\cdot,t))\tfrac{1}{r}\tfrac{\partial}{\partial r}\left(r\tfrac{\partial T(r,t)}{\partial r}\right)\\ &-2\cdot h^{-1}\cdot F(T(r,t)) + 2\cdot h^{-1}\cdot \sum_{l=1}^{L} G_l(r)u_l(t)\end{aligned} \tag{3}$$

$$T(r,0) = T_0(r),\ \ 0 \le r < R \tag{4}$$

$$[\partial T(r,t)/\partial r]_{r=R} = 0 \tag{5}$$

where R is the radius of the wafer; h is its thickness; radial position on the wafer is denoted by r; $T(r,t)$ denotes the temperature of the points on the wafer with radius r at time t; ρ is the density of the wafer material; the specific heat $c(T(\cdot,t))$ and thermal conductivity $k(T(\cdot,t))$ of the wafer are assumed to be functionals with respect to the temperature profile $T(\cdot,t)$, i.e. they may depend on temperature at various points of the wafer.

The notation $F(T)$ in (3) denotes *the emission function from the unit area of the surface of a body.* It is equal to $\sigma\epsilon T^4$ for a graybody with emissivity ϵ, where σ is the Stefan-Boltzman constant. A simple expression for the non-graybody emission function $F(T)$ was derived in [4]. The function $F(T)$ may also incorporate some additional phenomena, such as radiation exchange between different areas on the wafer and between the wafer and other parts of the RTP system.

In [5] we defined *the lamp ring radiation function* $G_l(r)$ *in* (3) *as the fraction of radiation power emitted by the* l^{th} *ring of the lamps reaching the unit area lying on the* *circular zone of the wafer between radii r and $r + dr$.* A method for calculating these functions, using the finite element model of an RTP system and MSC/NASTRAN, is given below.

The control function $u_l(t)$ in (3) is equal to the power emitted by the l^{th} ring of heating lamps. It may be calculated by the formula[5]:

$$u_l(t) = S_l F(W_l(t)), \ l = 1, \dots, L; \tag{6}$$

where, S_l is the area of the l^{th} lamp ring and $W_l(t)$ is the temperature of the l^{th} lamp ring at time t. Evidently, we must set:

$$u_l(t) \geq 0, \ l = 1, \dots, L. \tag{7}$$

The problem of heat control of the wafer is to find a control temperature of the lamp surface $W_l(t)$, $l = 1, \dots, L$ (or the control functions $u_l(t)$), such that the solution $T(r,t)$ of equations (3)-(7) *follows a given uniform reference temperature trajectory $\bar{T}(t)$.*

We may calculate the functions $G_l(t)$ using matrix $\mathbf{D}$ (cumulative radiation exchange coefficients between elements) given by formula (2) from the finite element model of the RTP system. Let $D_{i,j}$ be the cumulative radiation exchange coefficient from the j^{th} lamp element to the i^{th} wafer element in the finite element model; $\mathbf{\Phi}_l$ the set of elements of the finite element model belonging to the l^{th} lamp ring (Fig. 1); $\#(\mathbf{\Phi}_l)$ the number of elements in $\mathbf{\Phi}_l$; s_l the area of the lamp element from $\mathbf{\Phi}_l$; $\mathbf{\Psi}_n$ the set of elements of the finite element model belonging to the n^{th} circular wafer zone (Fig. 1); $\#(\mathbf{\Psi}_n)$ and the number of elements in $\mathbf{\Psi}_n$. Let r_n be some radius inside the n^{th} circular wafer zone. Assuming that the circular zones are sufficiently narrow, it was shown in [5] that

$$G_l(r_n) = \frac{\sum\limits_{i \in \mathbf{\Psi}_n} \sum\limits_{j \in \mathbf{\Phi}_l} D_{i,j}}{\#(\mathbf{\Psi}_n) \cdot \#(\mathbf{\Phi}_l) \cdot s_l} \tag{8}$$

Formula (8) represents a table of values of the functions $G_l(r)$, $l = 1, \dots, L$. These functions can be approximated by an analytical expression. Bessel function approximations are preferable in our context.

Calculation of $G_l(r_n)$ using MSC/NASTRAN involves the following steps:

Step 1. Calculation of matrix of view-factors $\mathbf{F}$, using the geometrical model of the RTP station and VIEW module and their adjustment for semitransparency of the quartz window by the method described in [7].

Step 2. Calculation of matrix $\mathbf{D}$ by formula (2) using DMAP. The structure of this matrix is shown in Fig. 2. It is divided into the blocks correspondent to cumulative exchange coefficients between the finite boundary finite elements of the lamps, wafer, chamber and quartz window.

Step 3. Deriving the block of the matrix $\mathbf{D}$, correspondent to lamps to wafer exchange using DMAP. The coefficients of this block are denoted by $D_{i,j}$ for cumulative exchange coefficient from the j^{th} lamp element to the i^{th} wafer element (see Fig. 1).

Step 4. Calculation of $G_l(r_n)$ using DMAP.

Step 5. Bessel approximation of the functions $G_l(r)$ given by the table of values $G_l(r_n)$, $n = 1, \ldots, N$. $l = 1, \ldots, L$.

Example[5]. Four functions $G_l(r)$ were calculated for different lamp ring configurations in our finite element model of the RTP system (Fig. 1). The values $G_l(r_n)$ for 11 circular wafer zones (dots on the Fig. 3) and Bessel functions approximation with 3 and 4 terms are presented in Fig. 3. Horizontal lines on the graphs are the first (constant) terms $G_{l,0}$ of the approximations. They are equal to the average values of the function along the wafer, i.e. $G_{l,0} = \frac{2}{R^2} \int_0^R rG_l(r)dr$.

4 Using MSC/NASTRAN in Design Procedure of Configuration of the Heating Lamps in an RTP System

Is was shown in [5] that, with some reasonable for an RTP system assumptions, the solution of the problem of heat control of the wafer, formulated above, is given by the formula:

$$u_l(t) = q_l \cdot \left[\frac{h}{2} \cdot \rho \cdot c(\bar{T}(t)) \cdot \frac{d\bar{T}(t)}{dt} + F(\bar{T}(t)) \right], \; l = 1, \ldots, L \tag{9}$$

where vector $(q_1, \ldots, q_L)'$ is the solution of the following system of linear equations

$$\begin{bmatrix} G_{1,0} & \ldots & G_{L,0} \\ G_{1,1} & \ldots & G_{L,1} \\ \vdots & \vdots & \vdots \\ G_{1,L-1} & \ldots & G_{L,L-1} \end{bmatrix} \cdot \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_L \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{10}$$

with coefficients $G_{l,n} = \frac{\int_0^R rG_l(r)J_0(\frac{\mu_n r}{R})dr}{\int_0^R r(J_0(\frac{\mu_n r}{R}))^2 dr}$ equal to n^{th} Bessel coefficient of the l^{th} lamp ring radiation function $G_l(r)$. Here $J_0(x)$ the Bessel function of the first kind of zero order, and $\mu_n \geq 0$, $n = 0, 1, \ldots$ are the sequential solutions (in increasing order) of the equation $\mu \frac{dJ_0(\mu)}{d\mu} = 0$.

We say that temperature uniformity is achievable for the RTP system with heat transfer described by equations (3), (4), (5), (6) if the solution $(q_1, \ldots, q_L)'$ of the equation (10) is nonnegative, i.e. $q_l \geq 0, l = 1, \ldots, L$.

Theorem [5]. *The necessary condition of achievability of temperature uniformity for an RTP system with heat transfer process described by equations (3), (4), (5), (6) is the following:*

$$\bigcup_{l=1}^{L} I_l^- = [0, R], \; \bigcup_{l=1}^{L} I_l^+ = [0, R] \tag{11}$$

where

$$I_l^- = \{r \in [0, R] | G_l(r) \leq G_{l,0}\}, I_l^+ = \{r \in [0, R] | G_l(r) \geq G_{l,0}\}, l = 1, \ldots, L$$

This condition is also sufficient for $L = 3$*, if* $dG_l(r)/dr \neq 0$ *for those* $r \in [0, R]$*, where* $G_l(r) - G_{l,0} = 0$*,* $l = 1, 2, 3$.

Condition (11) can be checked easily using the graphs of functions $G_l(r) - G_{l,0}, l = 0, \ldots, L$. Moreover, these graphs may guide one to figure out what changes should be made to the configuration of the lamp rings to meet this condition, if it is not satisfied for a given trial configuration. This allows the designer to carry out a systematic design procedure, described below.

Example [5]. The three lamp ring radiation functions (in $1/m^2$), graphed in Fig. 3 a, b and d, do not meet condition (11), as one can see from Fig. 4a. The three functions represented in Fig. 3 a, c and d do meet this condition (Fig. 4 b).

The main objective of design of an RTP system is *to make it possible to approach a uniform reference temperature profile along the silicon wafer.*

Block-diagram of a system for design of configuration of heating lamps in an RTP system is presented in Fig. 5. For a given (initial) configuration of the lamps we calculate matrix **D** (by formula (2)), using finite element model for this configuration and VIEW module of MSC/NASTRAN, and the lamp ring radiation functions (by formula (8)). Then we check the criterion of achievability of temperature uniformity by solving the equation (10) and/or by testing the condition (11) by visualization of the correspondent sets as illustrated in Fig. 4. If the criterion is met the control functions u_l are calculated by the formula (9) and heat transfer analysis using MSC/NASTRAN solution 159 is provided for the inspection of chosen configuration. If criterion is not met the graphs of the functions $G_l, l = 1, \ldots L$ visualized by computer-aided design interface guide the designer to figure out what changes should be made to improve the configuration. The improved configuration is directed to MSC/NASTRAN for subsequent iteration of design.

The MSC/NASTRAN solution 159 is provided for inspection of successful configuration that meet the criterion. In this case the time dependent temperatures of the lamp rings $W_l(t)$ are calculated by solving the equation (6). An example of representing the functions $W_l(t)$ in MSC/NASTRAN input file is the following:

```
$
$      TEMPERATURE ON THE OUTER RING
$
TABLED2,10,0.,,,,,,,+TAO
+TAO,0.,2070.5,6.,2100.7,11.,2166.2,15.,2255.6,+TTAO
+TTAO,20.,2417.5,25.,2629.1,30.,2878.7,ENDT
$
$      TEMPERATURE ON THE MIDDLE RING
$
TABLED2,11,0.,,,,,,,+TAM
+TAM,0.,1897.4,5.,1917.7,10.,1969.5,15.,2067.0,+TTAM
+TTAM,20.,2215.3,25.,2409.2,30.,2637.9,ENDT
$
$      TEMPERATURE ON THE INNER RING
$
TABLED2,12,0.,,,,,,,+TAI
```

```
+TAI,0.,867.6,6.,881.3,11.,908.7,15.,946.2,+TTAI
+TTAI,20.,1014.2,25.,1102.9,30.,1207.6,ENDT
$
```

Example of the design process. The configuration of the lamp rings in the RTP system (Fig. 1) can be defined by two parameters: radius R_l and height H_l. A design process may be the following:.

Step 1. We have chosen the following initial configuration of three lamps: $R_1 = 0, H_1 = 27.3cm,\ R_2 = 2.03cm, H_2 = 27.2cm,\ R_3 = 8.23cm, H_3 = 31.1cm$; corresponding lamp ring radiation functions are represented in Fig. 3 a, b, d.

Step 2. Criterion (11) is not met (Fig. 4a).

Step 3. One of the options to be applied in order to meet the criterion (as one can see from Fig. 3 a, b, d and understanding the behavior of functions $G_l()$ from their physical meaning) may be to move the lamp ring 2 into the position $R_2 = 5.72cm, H_2 = 31.2cm$.

Now we go again back to step 1 with the new configuration:

Step 1. Corresponding lamp ring radiation functions are shown in Fig. 3 a, c, d.

Step 2. Criterion (11) is met (Fig. 4b).

Step 3. We omit this step, because the configuration arrived at can be used to achieve a uniform tracking of the reference temperature profile.

Step 4. The Bessel approximations $G_l(r)\ , l = 1,2,3$ of the lamp ring radiation functions (in $1/m^2$) are the following: $G_1(r) = 23.071 + 68.105J_0(50.285r) + 52.328J_0(92.068r)$; $G_2(r) = 9.6146 + 1.4443J_0(50.285r) - 5.4243J_0(92.068r)$; $G_3(r) = 6.3663 - 1.3636J_0(50.285r) + 0.1173J_0(92.068r)$. The solution of equation $\begin{bmatrix} 23.071 & 9.6146 & 6.3663 \\ 68.105 & 1.4443 & -1.3636 \\ 52.328 & -5.4243 & 0.1173 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ is $\mathbf{q} = (3.821 \cdot 10^{-4}, 5.317 \cdot 10^{-2}, 7.540 \cdot 10^{-2})[m^2]$; the control law is represented by (9).

Step 5. This control law was tested for the following reference temperature

a. $\bar{T}(t) = 1000[K]$ (constant level);
b. $\bar{T}(t) = 300[K] + 30[K/s] \cdot t$ (constant ramp).

Results of the finite element simulation are given in Fig. 6a and 6b;

5 Discussion

A crucial problem in the design of an RTP system is to find a geometrical configuration of heating lamps allowing for effective control in approaching a uniform reference temperature profile along the silicon wafer. The criterion of achievability of temperature uniformity is used as a goal of design in the proposed interactive design procedure with MSC/NASTRAN modules in the kernel. Simulation results showed feasibility and effectiveness of such an approach to design of an RTP system. Its commercial implementation require some improvements in calculation and interface modules and effective automatization of information exchange between the modules.

Version 68 allows us to use wavelength and temperature dependent emissivity, which is very important for modeling heat processes in an RTP system. It utilizes emissivity as a piecewise constant function of wavelength. Emissivity in a form $\sum_{i=I_{\min}}^{I_{\max}} p_i(T)\lambda^l$ of generalized polynomial in wavelength with temperature dependent coefficients is more natural for an RTP system. As was shown in [4] in this case the emission function is $F(T) = \sum_{i=I_{\min}}^{I_{\max}} \alpha_i p_i(T)T^{4-l}$ with $\alpha_0 = \sigma$ (Stefan-Boltzmann constant), $\alpha_1 = 3.02 \times 10^{-10}[W/(mK^3]$, $\alpha_2 = 2.97 \times 10^{-12}[W/K^2]$, $\alpha_{-1} = 1.51 \times 10^{-5}[W/(m^3K^5)]$, $\alpha_{-2} = 5.15 \times 10^{-3}[W/(m^4K^6]$. Implementation of these formulas into MSC/NASTRAN is not difficult and it will improve an accuracy of RTP design.

Simulation of semitransparent bodies is very important for RTP. One approach for this simulation was developed in [7] and used in our design procedure. Its implementation into MSC/NASTRAN may improve this as well as many other design projects.

Much better graphical interface is needed to develop commercial interactive design procedure for RTP. At the present time MSC does not propose adequate pre- and post-processing tools for thermal analysis.

This design procedure was used to inspect the NJIT RTP system. Finite-element model of the system was developed and simulation showed that the criterion of achievability of temperature uniformity is not satisfied and, hence, this system cannot be used for production. An experimental inspection, based on estimation of parameters of the system proved this conclusion. Possible local improvements were proposed by the design procedure described above.

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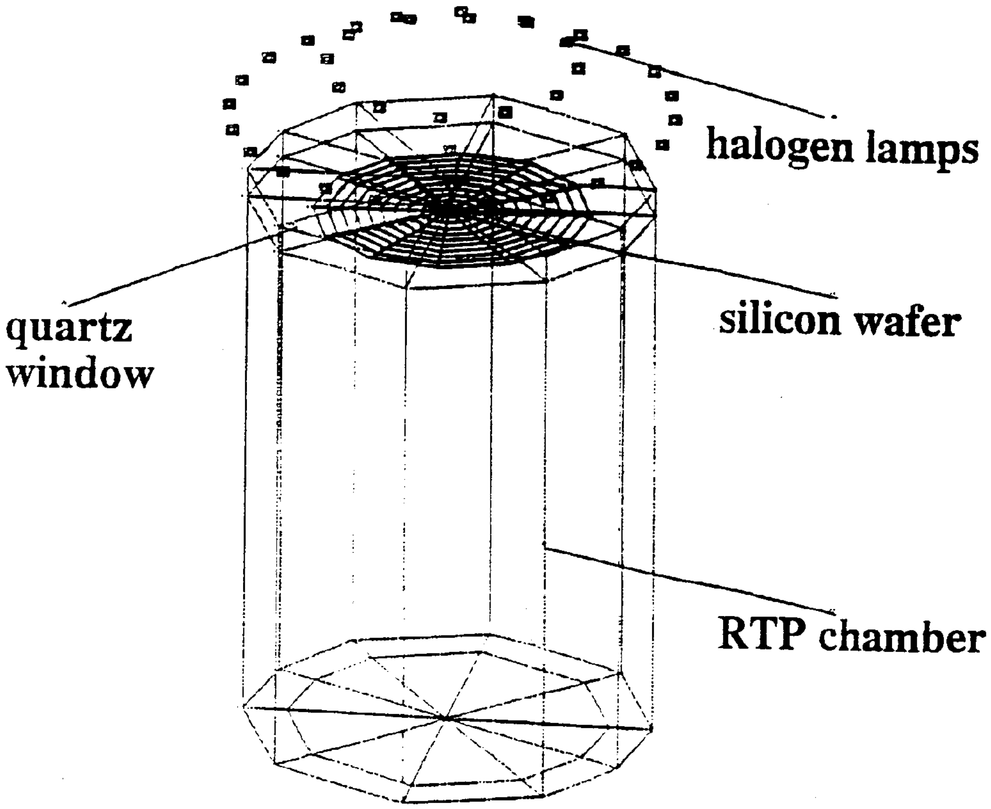
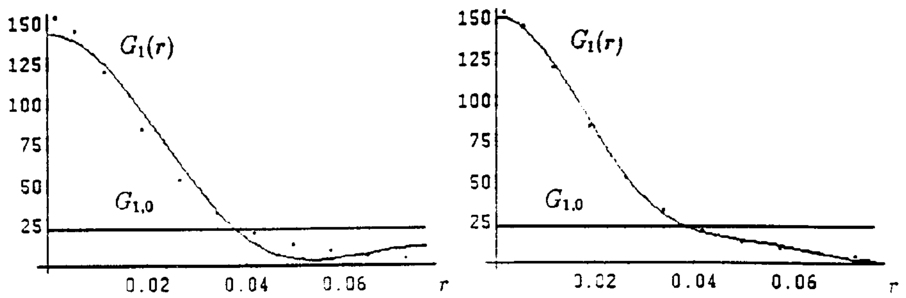


Figure 1. The geometry of the finite element model of the RTP system

	Lamps	Wafer	Chamber	Quartz wndow
Lamps				
Wafer	$D_{i,j}$			
Chamber				
Quartz wndow				

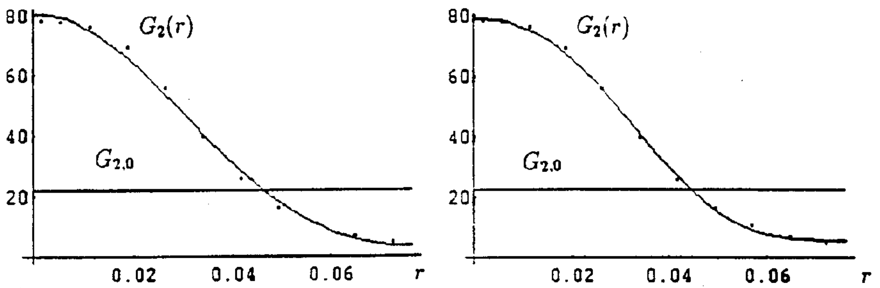
Figure 2. Dividing of matrix **D** (cumulative exchange coefficients) on blocks corresponding to the main parts of an RTP station



Approximation by 3 Bessel functions

Approximation by 4 Bessel functions

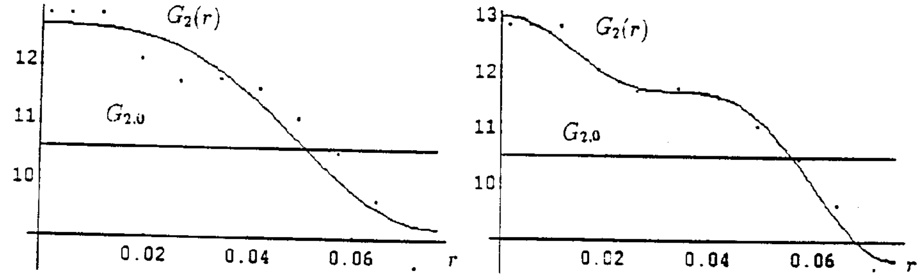
a. Lamp ring 1



Approximation by 3 Bessel functions

Approximation by 4 Bessel functions

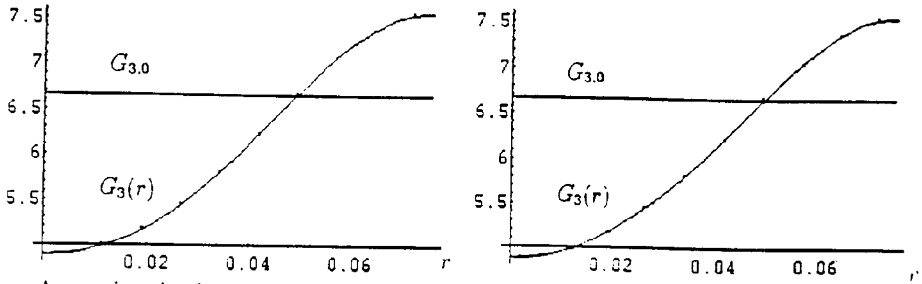
b. Lamp ring 2 (first try)



Approximation by 3 Bessel functions

Approximation by 4 Bessel functions

c. Lamp ring 2 (second try)



Approximation by 3 Bessel functions

Approximation by 4 Bessel functions

d. Lamp ring 3

Figure 3. Lamp ring radiation functions $G_l(r)$

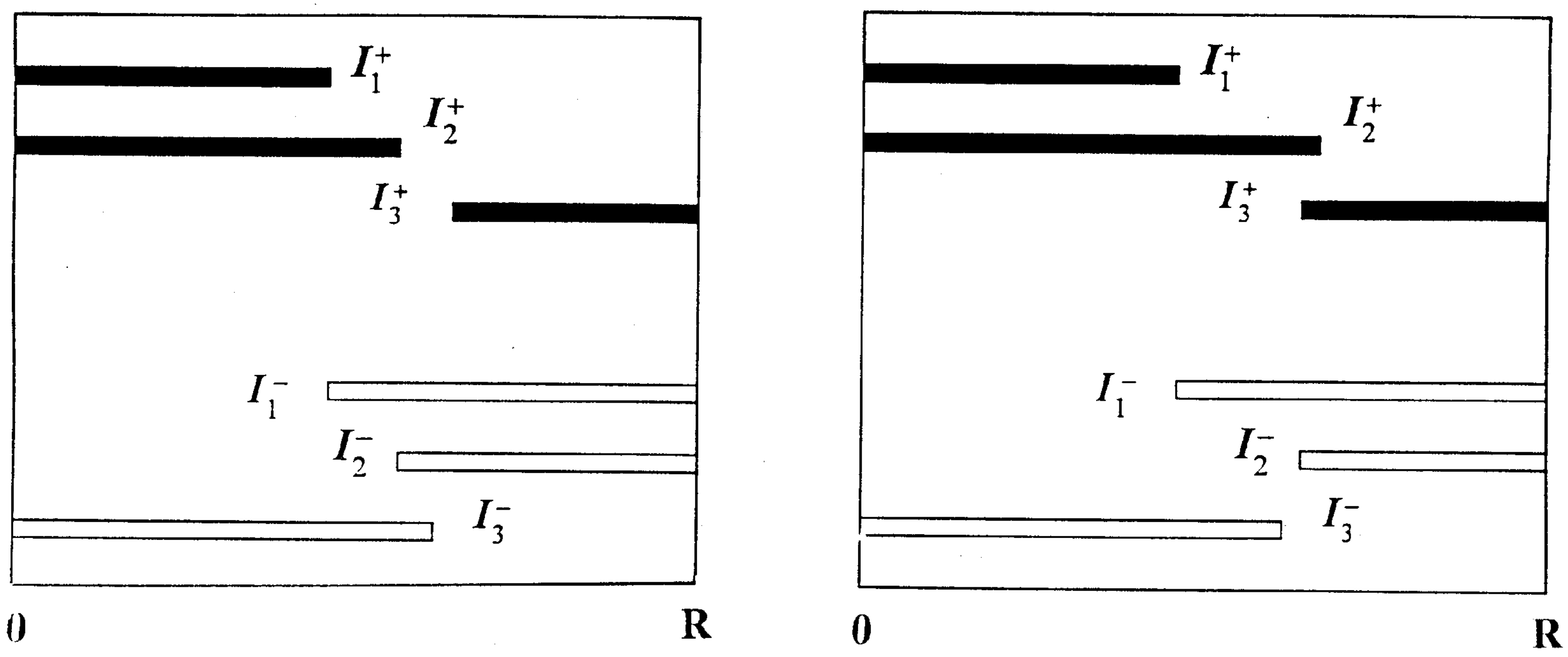


Figure 4. Sets for the condition of temperature uniformity:
(a) Non satisfactory condition; (b) Satisfactory condition

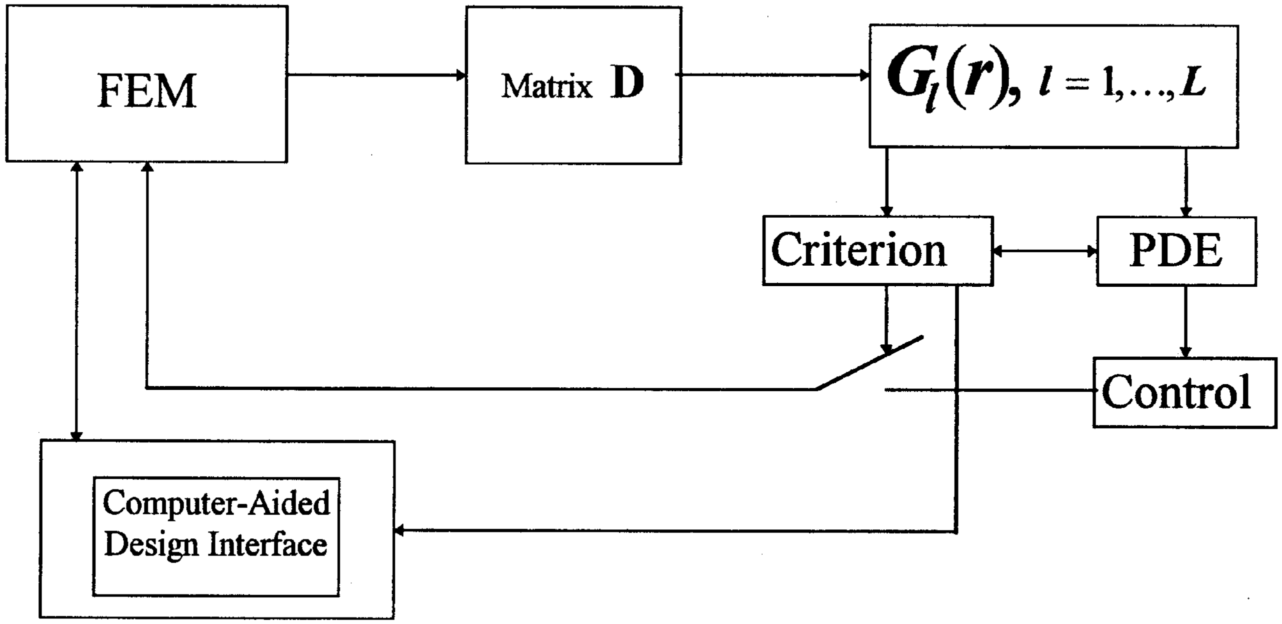


Figure 5. Block-Diagram of a system for RTP design

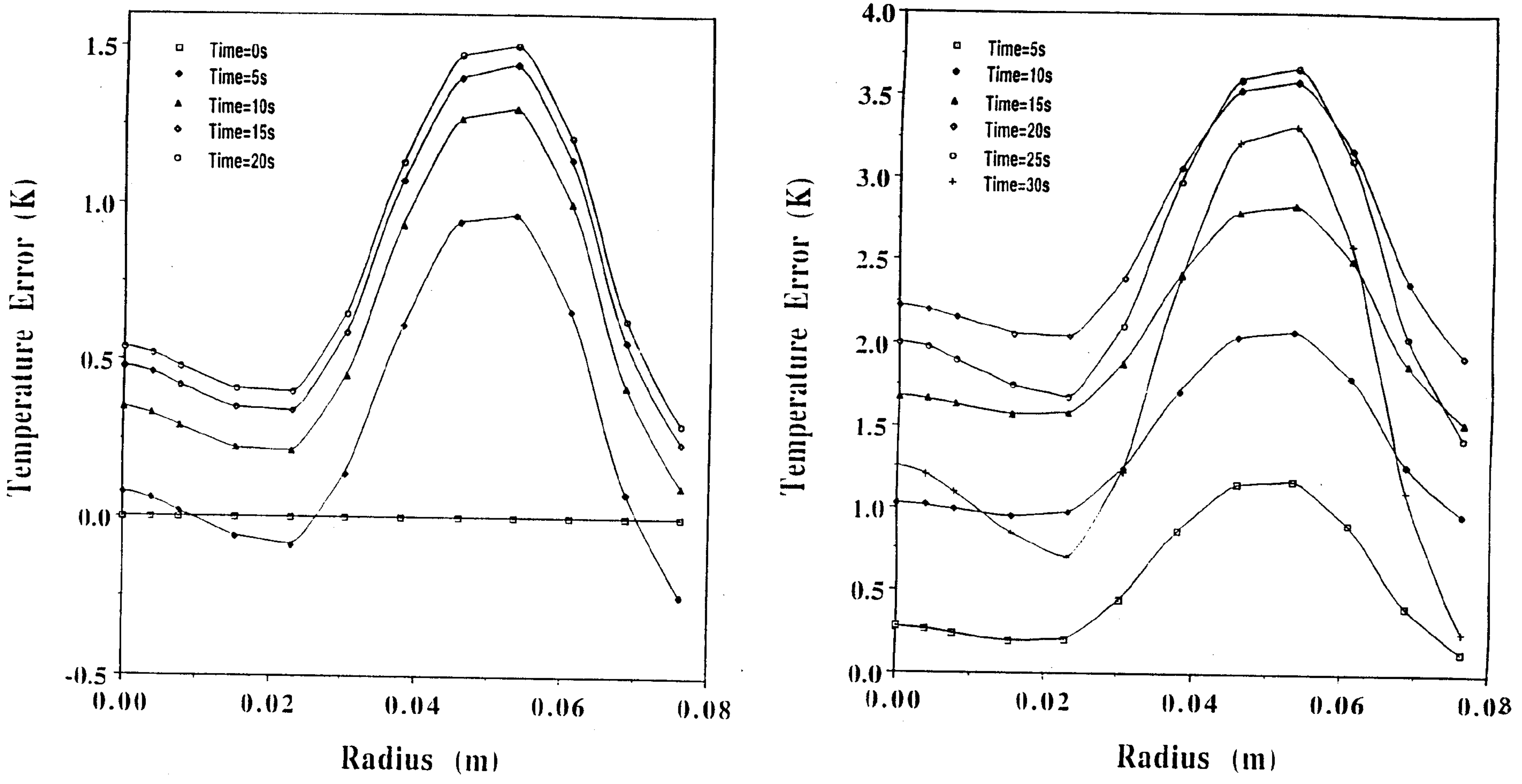


Figure 6. Radial temperature nonuniformity:
(a) for the constant level of 1000*K*; (b) for the ramp of 30*K/s*