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THE INFLUENCE OF WAVELENGTH-DEPENDENT RADIATION IN SIMULATION OF LAMP-HEATED RAPID THERMAL PROCESSING SYSTEMS

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Understanding the thermal response of lamp-heated rapid thermal processing (RTP) systems requires understanding relatively complex radiation exchange among opaque and partially transmitting surfaces and materials. The objective of this paper is to investigate the influence of wavelength-dependent radiative properties. The examples used for the analysis consider axisymmetric systems of the kind that were developed by Texas Instruments (TI) for the Microelectronics Manufacturing Science and Technology (MMST) Program and illustrate a number of wavelength-dependent (spectral) effects. The models execute quickly on workstation class computing platforms, and thus permit rapid comparison of alternative reactor designs and physical models. The fast execution may also permit the incorporation of these models into real-time model-based process control algorithms.

INTRODUCTION

This paper describes a physical model of axisymmetric rapid thermal processing (RTP) reactors of the kind developed by Texas Instruments for the Microelectronics Manufacturing Science & Technology (MMST) program. Then, using simulations based on this model, we illustrate the effects of wavelength-dependent (spectral) thermal-radiation transport. Spectral-radiation behavior can be an important consideration in semiconductor processing equipment, especially in lamp-heated systems that have partially transmitting components like quartz windows and the silicon wafer itself.

The RTP-reactor model, as shown in Fig. 1, consists of two coupled components. The window, which separates the lamp housing from the reaction chamber, and the wafer are represented by a radial one-dimensional transient thermal energy equation that describes thermal conduction within the wafer and window, convective heat transfer at the top and bottom faces, and thermal radiation exchange between the window, the wafer, and the other features in the system, including the lamp housing and reactor walls. The second component of the model is the spectral radiation model. This model considers the complex radiation exchange between all the surfaces in the reactor, including internal reflections within partially transmitting media. It considers the radiative energy transport in wavelength bands. The radiation model provides net radiative fluxes to the top and bottom surfaces of the wafer and window, as well as internal heating due to energy absorption. The coupling between the model components is via the radiative energy fluxes to the window and wafer.

Because the differential-equation part of the model is essentially one dimensional, the model executes quickly even on workstation class computing platforms. Thus, in addition to understanding spectral-radiation effects, the model may also have value in design and real-time control applications.

Prior work. The simulation of RTP systems has generally followed two approaches. Some (cf. Jensen, et al. [1] and other authors [2], [3], [4], [5], [6]) have developed two- and three-dimensional finite-element or finite-volume approaches to model the heat transport and coupled fluid flow in the reaction chamber. Here, the radiation exchange is handled through radiation view or exchange factors. Most work in this area considers gray-diffuse view factors, although Jensen, et al. [1] also consider specular reflection in their exchange factors. Gray-diffuse view factors are calculated by ge-

ometry. Typically, the specular exchange factors are calculated using Monte-Carlo, ray-tracing software. The finite-element models probably have their greatest utility in design optimization, especially resolving complex-geometry issues.

The second approach to RTP modeling is motivated by process control issues [7], [8], [9]. Here, the models consider only one-dimensional conduction in the wafer, with convective and radiative heat fluxes considered at the wafer surfaces. The radiation is computed in terms of geometric gray-diffuse view factors that couple the lamp system to the wafer. These models run very fast and are used as the basis for designing the real-time control algorithms. The present paper generally follows this second approach, but provides a significant improvement for non-gray wavelength-dependent radiation.

Spectral Radiation. Because radiation is an electromagnetic wave, models of radiative energy transport should consider spectral (wavelength-dependent) and directional features. In engineering applications, the conventional practice has been to deal with radiative heat transfer between surfaces that can be characterized as diffuse reflectors and diffuse emitter-absorbers. In this way, the problem of diffuse surface interchange reduces to a geometric problem of determining the view factors between all interacting surfaces. By considering diffusely emitting and reflecting surfaces, the directional effects are eliminated (refer to the discussion section). Thus, the values of surface radiation properties (emissivity, transmissivity, and reflectivity) depend on the wavelength, thermodynamic state (e.g., temperature and composition or mole numbers) and the morphology of the surface (e.g., surface roughness). In other words, the radiation emitted, reflected, transmitted and absorbed by a solid body depends on the radiative properties of the material, temperature of the body, viewing direction and the surface conditions.

Most engineering simulations simplify radiative transport by considering only wavelength-independent radiation (gray-diffuse) or some kind of indirect way to estimate roughly the wavelength-dependent effects. However, the spectral emissivity plays the important role in the behavior of radiative heat exchange between materials. Over the visible and infrared region of the electromagnetic spectrum, the spectral emissivity of metals usually decreases moderately with increasing wavelength while that for nonmetals usually increases [10].

For radiation heat flux at each surface, our non-gray model treats radiative heat exchange in each wavelength band individually, then

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integrates the contribution in all wavelengths into a compound radiation energy. The spectral radiation model is fully three-dimensional in so far as the geometric view factors consider three-dimensional geometries. Even though we consider complex geometries for the radiation exchange, our model is essentially simplified by considering only one-dimensional energy transport in the wafer and window.

While our model considers spectral radiation exchange in great detail, it does not directly consider specular reflections. A diffuse reflector is a surface whose bi-directional reflectivity is independent of reflectance angle; and a diffuse emitter-absorber is a surface whose directional reflectivity (absorptivity or emissivity) is independent of incidence angle. The assumption of radiation diffusely emitting and reflecting surfaces is reasonable in the fact that many reflections and rereflections within an enclosure tend to average out radiative nonuniformities even when there are very smooth surfaces in the enclosure. For many practical problems, the diffuse analysis is actually valid and will give satisfactory results. The assumptions of diffuse surfaces is not valid for the enclosure with very "irregular" geometry such as long, narrow cracks with smooth surfaces, which need to be treated as specular reflectors by special approaches, such as Monte-Carlo or ray-tracing methods [1], [10].

THE FORMULATION OF THE MODEL

Fig. 1 shows a sketch of the axisymmetric-reactor layout that we consider. Several ring-shaped lamps (possibly including a center lamp) are located at the top of the lamp housing. A quartz window separates the wafer (and wafer support) from the lamp arrays. Unit vectors r, z define the cylindrical coordinate system with the r -axis along the wafer starting from the center of wafer, and with the z -axis along the symmetric axis. The wafer (and its support structure) and the quartz window are discretized radially into elements for which temperature is the dependent variable. Radiative heat flux exchange among all surfaces inside the reactor is evaluated. The surfaces include those of lamp arrays, chamber walls, and both sides of wafer, wafer support, and quartz window.

Wavelength-Dependent Radiation Model. The following discussion defines the equations that describe the exchange of thermal radiative energy. Net heat flux per unit wavelength λ at each surface is:

$$\begin{aligned} \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{net}} &= \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{incoming}} - \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{emission}} \\ &\quad - \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{reflection}} - \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{transmission}} \\ &= \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{absorption}} - \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{emission}} \end{aligned}$$

The incoming heat flux per unit wavelength λ at any surface element k consists of heat fluxes coming from all surface elements in an enclosure, i.e.,

$$A_k \left(\frac{dq(\lambda)}{d\lambda} \right)_{k \text{ incoming}} = \sum_j S_{jk} A_j \left(\frac{dq(\lambda)}{d\lambda} \right)_{j \text{ outgoing}},$$

where A_j is the surface area of element j , S_{jk} is the view factor from element j to element k . Due to the reciprocity rule $A_j S_{jk} = A_k S_{kj}$, the above equation can be rewritten as

$$\left(\frac{dq(\lambda)}{d\lambda} \right)_{k \text{ incoming}} = \sum_j S_{kj} \left(\frac{dq(\lambda)}{d\lambda} \right)_{j \text{ outgoing}}.$$

The outgoing heat flux per unit wavelength λ at any surface element k for a nonopaque media consists of three contributions:

the heat flux emitted from surface, the heat flux reflected by the surface, and the heat flux transmitted through the surface from the under side of the surface element. For an opaque material, only two contributions,

$$\begin{aligned} \left(\frac{dq(\lambda)}{d\lambda} \right)_{k \text{ outgoing}} &= \\ &= \begin{cases} \epsilon_k e_{\lambda b}(\lambda, T_k) + \rho_k \left(\frac{dq(\lambda)}{d\lambda} \right)_{k \text{ incoming}} & \text{opaque case} \\ E_k e_{\lambda b}(\lambda, T_k) + Re_k \left(\frac{dq(\lambda)}{d\lambda} \right)_{k \text{ incoming}} \\ \quad + Tr_{k'} \left(\frac{dq(\lambda)}{d\lambda} \right)_{k' \text{ incoming}} & \text{nonopaque case} \end{cases} \end{aligned}$$

The variables ϵ_k , ρ_k , T_k are emissivity, reflectivity and temperature for surface k , respectively. Re_k , E_k are fractions of incoming energy reflected and absorbed at surface k of a nonopaque medium. $Tr_{k'}$ is the fraction of energy that is transmitted through (the under side of) surface k from surface k' , where k' denotes the opposing surface of the same nonopaque volume element. The spectral distribution of emissive power for a blackbody is given by Planck's law as

$$e_{\lambda b}(\lambda, T) = \frac{2\pi C_1}{\lambda^5 (\exp(C_2/(\lambda T)) - 1)},$$

where C_1 and C_2 are Planck's constants.

By combining above expressions, the thermal-energy balance for an enclosure provides the following vector-matrix equation for the incoming radiative flux per unit wavelength λ for all surface elements in the enclosure.

$$\begin{aligned} \left(\frac{dq(\lambda)}{d\lambda} \right)_{\text{incoming}} &= [\mathbf{I} - \mathbf{S} \text{diag} \mathbf{R}_e(\lambda) - \mathbf{S}_1 \text{diag} \mathbf{T}_r(\lambda)]^{-1} \\ &\quad * \mathbf{S} \text{diag}(\mathbf{E}(\lambda) e_{\lambda b}(\lambda, T)), \end{aligned}$$

where $\mathbf{I}$ is the identity matrix, T is temperature, $\mathbf{S}$ is the view factor matrix, $\mathbf{S}_1$ is related to $\mathbf{S}$ and will be explained later, $\mathbf{R}_e(\lambda)$ is the reflection matrix, $\mathbf{T}_r(\lambda)$ is the transmission matrix, and $\mathbf{E}(\lambda)$ is the emission-absorption matrix.

The reflection matrix $\mathbf{R}_e(\lambda)$ is a diagonal matrix that represents the fraction of energy impinging on a surface that is reflected. For the surface of a nonopaque medium, $\mathbf{R}_e(\lambda)$ must represent the result of multiple internal reflections and is given by [11],

$$\mathbf{R}_e(\lambda) = \rho(\lambda) \left[1 + \frac{(1 - \rho(\lambda))^2 (\tau(\lambda))^2}{1 - (\rho(\lambda))^2 (\tau(\lambda))^2} \right]$$

where $\rho(\lambda)$ is the reflectivity and $\tau(\lambda)$ is the transmissivity. The elements of $\mathbf{R}_e(\lambda)$ that correspond to an opaque surface are simply the reflectivity of that surface, i.e., $\mathbf{R}_e(\lambda) = \text{diag } \rho(\lambda) = \mathbf{I} - \text{diag } \epsilon(\lambda)$, where $\epsilon(\lambda)$ is the emissivity.

The transmission matrix $\mathbf{T}_r(\lambda)$ is a diagonal matrix that represents the fraction of energy impinging on a surface that is transmitted. For the surface of a nonopaque medium, the transmission must account for multiple internal reflections,

$$\mathbf{T}_r(\lambda) = \frac{(1 - \rho(\lambda))^2 \tau(\lambda)}{1 - (\rho(\lambda))^2 (\tau(\lambda))^2}.$$

The elements of $\mathbf{T}_r$ that correspond to an opaque surface are zero.

The emission-absorption matrix $\mathbf{E}(\lambda)$ is a diagonal matrix that represents the fraction of energy impinging on a surface that is absorbed by the surface. As the result of multiple reflections in a nonopaque media,

$$\mathbf{E}(\lambda) = \frac{(1 - \rho(\lambda))(1 - \tau(\lambda))}{1 - \rho(\lambda)\tau(\lambda)}.$$

The elements of $E(\lambda)$ that correspond to an opaque surface are simply the emissivity of that surface, i.e., $E(\lambda) = \text{diag } \epsilon(\lambda)$. It is worth noting that according to Kirchhoff's law the emission matrix and the absorption matrix are equivalent, even for nonopaque media [11].

Because $\rho(\lambda) + \tau(\lambda) + \epsilon(\lambda) \equiv 1$, we note that the above expressions must satisfy

$$R_e(\lambda) + T_r(\lambda) + E(\lambda) \equiv I.$$

In the vector-matrix equation describing net heat flux per unit wavelength at the surfaces, $(dq(\lambda)/d\lambda)_{\text{incoming}}$, the matrix S_1 is related to view factor matrix S in such a way that $(S)_{i,j_1} = (S_1)_{i,j}$, where (j, j_1) denote the opposing pairs of surface elements that define a volumetric element of a layer of nonopaque medium. In our model, the top and bottom surfaces of the wafer and the window are such opposing surfaces.

Integrating over all wavelengths, the total heat flux to each surface is given by

$$\begin{aligned} Q_{\text{rad}}(T) = & \int_0^{\lambda_{\text{max}}} \text{diag} A \left\{ \text{diag} E(\lambda) [I - S \text{diag} R_e(\lambda) - S_1 \text{diag} T_r(\lambda)]^{-1} S - I \right\} \\ & * \text{diag}(E(\lambda) e_{\lambda b}(\lambda, T)) d\lambda \\ & + \text{diag} A \left\{ \text{diag} E(\lambda_{\text{max}}) [I - S(I - \text{diag} \epsilon(\lambda_{\text{max}}))]^{-1} S - I \right\} \\ & * \text{diag} E(\lambda_{\text{max}}) [1 - F] \sigma T^4 \end{aligned}$$

where A is the diagonal matrix of surface-element areas,

$$F = \frac{1}{\sigma T^4} \int_0^{\lambda_{\text{max}}} e_{\lambda b}(\lambda, T) d\lambda,$$

is the fractional blackbody emission, and λ_{max} is the wavelength after which the surface becomes opaque, $\tau = 0$, and $\epsilon = \text{constant}$. The second term in the $Q_{\text{rad}}(T)$ equation represents the contributions from all wavelengths beyond λ_{max} .

Numerically, we evaluate the integrals by using the trapezoidal rule,

$$\int_0^{\lambda_{\text{max}}} f(\lambda) d\lambda \approx \frac{1}{2} \sum_{n=1}^{N-1} (f_n + f_{n+1}) (\lambda_{n+1} - \lambda_n).$$

Each wavelength band is defined by $(\lambda_{n+1} - \lambda_n)$, where N is the number of wavelength bands considered. The integrand in the above equations is represented here simply as $f(\lambda)$. The wavelength range of each band depends on the radiative properties considered. The model permits arbitrary wavelength banding, but we rarely use more than fifteen.

The equation representing the vector of net radiative fluxes to all surface elements, $Q_{\text{rad}}(T)$ can be interpreted physically

$$\begin{aligned} Q_{\text{rad}}(T) = & \underbrace{\int_0^{\infty} \text{diag} A \text{diag} E(\lambda) [I - S \text{diag} R_e(\lambda) - S_1 \text{diag} T_r(\lambda)]^{-1} S \text{diag} E(\lambda) e_{\lambda b}(\lambda, T) d\lambda}_{\text{absorbed flux}} \\ & - \underbrace{\int_0^{\infty} \text{diag} A \text{diag} E(\lambda) e_{\lambda b}(\lambda, T) d\lambda}_{\text{emitted flux}} \end{aligned}$$

Wafer and Window Energy Balance. The above wavelength-dependent radiation model is general, and it can be adopted into any (two- or three-dimensional) thermal system. Radiation heat flux at surfaces generally provides the surface thermal boundary conditions of the system. Since our model considers only one-dimensional (radial) thermal conduction in the wafer (and its support) and window, the thermal-energy balance in the wafer and window form a one-dimensional partial differential equation (PDE) system with radiation heat flux at the surfaces serving as a heat-source (or -sink) term in the equation for the element on which the surface resides. The thermal energy balance also considers thermal convection due to flowing gas at the surfaces. Here again, the convective fluxes are treated mathematically as source terms in the one-dimensional thermal energy equation. Therefore, the matrix-form of thermal energy equation for all elements of wafer and window is stated as

$$\begin{aligned} C \frac{\partial T}{\partial t} &= Q'_{\text{rad}}(T) + Q_{\text{cond}}(T) + Q_{\text{conv}}(T), \\ Q'_{\text{rad}}(T) &= Q_{\text{rad}}^{\text{top}}(T) + Q_{\text{rad}}^{\text{bot(tom)}}(T) \left(+ Q_{\text{rad}}^{\text{edge}}(T) \right) \end{aligned}$$

where C is the heat capacity vector, $C = \rho c_p V$; ρ is the mass density, c_p is specific heat, and V is the volume. The radiation contributions at the top and bottom surfaces are evaluated from the wavelength-dependent radiation model. The radiation heat flux at wafer edge gives a boundary condition for cases without ring support, so that it is added only to the edge element of the wafer.

The radial conduction is represented by the discrete (finite difference) form of

$$Q_{\text{cond}} = \frac{\partial}{\partial T} \left(k(T) A(r) \frac{\partial T}{\partial r} \right),$$

where $A(r)$ is the cross-sectional area of window or wafer and $k(T)$ is the thermal conductivity. The discrete form consists of a tri-diagonal matrix multiplied by the temperature vector. Symmetric boundary conditions are applied at the center of wafer and window. At the centerline, a zero-heat-flux condition is maintained. At the edge of the window a fixed-temperature condition is applied. At the edge of the wafer a variety of boundary conditions can be applied. Either fixed-temperature, insulated boundary condition or radiation heat exchange are applied at support/wall interface if there is a ring-support, and radiation heat flux is applied at wafer edge if the wafer is supported on pins. A thermal contact resistance or radiation heat exchange is applied at wafer-support interface for ring-support cases.

Convection at the top and bottom surfaces is represented by

$$Q_{\text{conv}} = -h(p, T) A_s(r) (T - T_{g,as}),$$

where $A_s(r)$ is the surface area, $h(p, T)$ is pressure- and temperature-dependent convection coefficient which can be found from empirical correlations or can be determined from simulations of the gas flow in the reaction chamber. $T_{g,as}$ is the temperature of the gas at the surface. The discrete form of convection term consists of a diagonal matrix multiplied by the temperature vector.

Lamp Power. The radiation model assumes that the lamps can be modeled as a surfaces in the radiation enclosure. Therefore, we need to provide a relationship between the lamp temperature and the applied lamp power. We assume that the lamp power and temperature are related as follows,

$$P = A \sigma (T^4 - T_{\text{wall}}^4),$$

where P is the lamp power, A is the lamp area, σ is the Stefan-Boltzmann constant, T is the lamp temperature and T_{wall} is the chamber wall temperature. For the simple case that the lamps are flat cylindrical

rings at the top of the chamber (Fig. 1), the area of each lamp ring is $A = \pi(r_o^2 - r_i^2)$, where r_o and r_i are the outer and inner radii of the lamp ring.

Numerical Solution. The coupled PDE system is solved by using the DASSL software [12], [13], [14]. It uses a general method-of-lines approach to convert the PDE system to a coupled ODE system. DASSL is designed to solve stiff differential-algebraic systems (DAE) of the form $g(t, y, y') = 0$, rather than $y' = f(t, y)$. DASSL is a variable-order method based on the backward-differentiation-formula (BDF) methods that were first popularized by Gear [15]. DASSL uses error-estimation methods to choose a sequence of time steps that controls local truncation error.

All simulations use 11 radial elements each to represent the wafer and the window.

DETAILS AND VALIDATION OF MMST MODEL

Reactor Geometry. For the example problems discussed in the following sections, the reactor radius is 12.0 cm, the lamp-to-window separation is 4.9 cm, the window-to-wafer separation is 0.165 cm, and the wafer-to-showerhead (bottom of reactor) is 3.43 cm. The quartz window thickness is 12.7 cm and the silicon wafer thickness is 0.635 mm. There are four lamp rings at the top of the reactor; the center radii are 2.223 cm, 5.08 cm, 7.84 cm, and 10.9 cm. Each lamp ring has a width of 1.5 cm. A graphite wafer support spans the distance from the wafer edge to the reactor wall. The view factors are calculated analytically. We have also combined the model with externally generated numerical view factors to treat more complex reactors. This model described above is capable of predicting radiation effects in three dimensional geometries.

Material Properties. The mass densities of the wafer, window, and support are 2330, 2200, and 7801 kg/m³ respectively. The thermal conductivity of the window is held constant at 1.38 W/m-K. The specific heat of the window is held constant at 744.8 J/kg-K. Figs. 4 and 3 show the temperature-dependent conductivities and specific heats for silicon and graphite.

For most of the simulations, we consider the band-dependent emissivity of stainless-steel as shown in Fig. 8. The emissivity of the graphite support is fixed at 0.95. We use a fixed emissivity of 0.05 to represent the reflector material at the top of the chamber. We take the emissivity of the lamps to be that of tungsten, $\epsilon = 0.45$ or as a function of wavelength (Fig. 9). Fig. 6 shows the transmissivity and refractive index for quartz; for most simulations, we use this data to determine the wavelength-dependent quartz emissivity, in one simulation, quartz emissivity is determined by $0.8 * (1 - \tau)$, in another simulation it is fixed at $(1 - \tau - \rho)$ where reflectivity is taken as 0.05. All simulations use the wavelength-dependent transmissivity of quartz as shown in Fig. 6. The wavelength- and temperature-dependent silicon-wafer emissivity from Sato [16] is shown in Fig. 5. Fig. 7 shows the wavelength- and temperature-dependent silicon-wafer transmissivity.

All the wavelength-dependent simulations use 14 bands that are defined to capture features of the wavelength-dependent material properties. Specifically, the bands are divided at wavelengths of 0, 0.17, 0.3, 0.4, 0.6, 1.1, 2.3, 2.6, 3.2, 3.5, 4.0, 4.2, 8.0, 15.0, and ∞ μ m. In spite of the fact that the window is effectively opaque beyond 4.2 μ m, we still observe contributions to the wafer response from the longer wavelengths.

Model Validation. The model was compared to data from tests some at Texas Instruments, where step power changes are applied to individual lamp rings. Fig. 2 shows data from one such test compared

to model predictions. In this test only zone two, the maximum power of which is 11 kW, was varied in the following way. From 0 to 67 seconds 20% power was applied, from 67 to 127 seconds the power was 30%, from 127 to 190 seconds the power was 40%, from 190 to 250 seconds the power was 50%, from 250 to 324 the power was 60%, and from 324 to 364 seconds the power was 70%. The initial temperature for the entire system 300°C. The model maintains wall temperatures at 27°C throughout, although there is some ambiguity about the experimental wall temperatures at the start of the tests. The model applied no convective heat transfer on either the wafer or the window. An interface resistance of 0.1 W/m-K between the wafer and the support is used.

Fig. 2 shows a comparison of model predictions to the wafer center (upper curve) and edge temperature as measured by wafer-embedded thermocouples. Initially, there is an offset between the predicted and measured temperatures, but the comparison is satisfactory near the operating temperatures. Some of the disagreement at early times is due to uncertainty about the starting conditions in the experiment. Overall, we find that the agreement between the model predictions and many such experiments is quite satisfactory. We feel that the model can be applied with confidence to understand the effects of various approximations in the radiation modeling, as discussed in the following section.

ILLUSTRATION OF SPECTRAL-RADIATION EFFECTS

The objective of this section is to illustrate the effects of various modeling approximations. The approach is to select (somewhat arbitrarily) a set of lamp-power trajectories, and then compare the wafer-temperature response under different sets of assumptions in the model.

For all the comparisons, the lamp zones are powered in the following way. Moving out radially, the maximum power in each of the lamp rings is 4, 10, 10, and 45 kW respectively. All zones begin at 0% power and are increased linearly to 100% at 10 seconds then remain at this power level after 10 seconds. The calculated lamps temperature at 10 s are 2406, 2460, 2208, 2961 K from zone 1 to zone 4, respectively (zone 1 is the inner ring). In all cases, the initial wafer and window temperature is 300 K.

There are six simulations to compare. (1) A full band simulation considers all the wavelength-dependent radiative properties of the nonopaque wafer, nonopaque window, nongray stainless-steel chamber wall and nongray lamps (or nongray tungsten). Four of the simulations are the same as the full-band simulation, except that each has one less wavelength-dependency in the model: (2) has an opaque wafer instead of a partially transmitting wafer, (3) has a gray chamber wall instead of a nongray chamber wall, (4) has gray lamps instead of nongray lamps, and (5) does not use the window refractive index to determine the emissivity of the quartz window. Finally, (6) is a single-band simulation, in which the emissivity of the wafer is only a function of temperature (shown in Fig. 10), the transmissivity of the quartz window is fixed at 0.85 at the lamp side and at 0.7 at the wafer side, the emissivity of the window is taken as $0.8 * (1 - \tau)$, the emissivities of stainless-steel chamber walls and tungsten are 0.3 and 0.45, respectively. For all six simulations, a radiation heat exchange boundary condition is applied at the wafer/support and support/wall interfaces.

Figure 11 compares the wafer center temperature versus time for all six simulations. The case with gray lamps has a higher ramp-up speed and higher final wafer temperature. The single-band case has a lower ramp-up rate initially, then a higher ramp-up rate later, and reaches a higher temperature at 13.3 s. The other four cases predict essentially the same response for the wafer center. The partially

transmitting wafer (case 1,3,4 and 5) and nongray chamber wall (case 1,2,4 and 5) have relatively small effects (within 50K). In addition, the temperature difference caused by not using the window refractive index (case 5) falls in a similar narrow range, so our simple expression for window emissivity may be a good alternative.

Figures 12 and 13 compare the temperature profiles of the wafer for all cases at $t = 7$ and 13.3 s, respectively. The scale used on these plots better shows the differences between all the simulations. Temperature varies by less than 25 K across the wafer. It is higher at the wafer edge due to the very high power used in zone 4. Of course, when the system is operated under closed-loop control the radial temperature profiles would be flat.

Figure 14 shows the radiation heat fluxes at the wafer for the full-band case at $t = 13.3$ s. The total incoming flux (including multiple reflections in the reactor and multiple internal reflections in the wafer and window media) comes mainly through the wafer top, with relatively low flux at the wafer bottom. The absorbed flux (total incoming flux multiplied by absorptivity) minus the total emitted flux (from top and bottom surfaces) is the net radiative heat flux to the wafer.

Figure 15 shows the total net radiation flux (absorbed flux minus emitted flux) at the wafer for all cases at $t = 13.3$ s. The opaque-wafer case has a higher net heat flux than all the cases with a nonopaque wafer. This is expected because a portion of the incident flux is transmitted through the nonopaque wafer. The gray-lamps case has the lowest flux, but it results in the highest wafer temperature (Figs 12-13). The single-band case has the highest flux since the customary radiative properties used there seem to overestimate the wafer emissivity, window transmissivity and lamp emissivity. The case with no window refractive index has a higher net flux than that for the full-band case, which means the window reflectivity in this case is less than that calculated from the simple expression $0.2 * (1 - \tau)$.

Figures 16 and 17 show incoming and net radiation flux at the wafer center over all wavelengths. The peak incoming flux at the wafer's top surface is very high and is at very short wavelengths, about 1.1 microns, while at the bottom surface the incoming flux is much lower and is at longer wavelengths, about 2.3 microns. In addition, the top flux is concentrated in a very narrow band due to the very high temperature of the lamps, while the bottom flux spreads over a wider wavelength range due to the relatively low temperature of the lower chamber walls. It is interesting to note that the net radiation flux has a negative contribution from 2.6 microns to 8 microns. This means the absorbed heat flux in this mid-wavelength range is not enough to offset the emission flux. Therefore, the main contribution for heating the wafer is from short wavelength radiation, i.e., less than 2.6 microns.

CONCLUSIONS

The wavelength-dependent analysis predicts the spectral distribution of incoming and absorbed radiation heat fluxes in different wavelength bands to the wafer in a RTP reactor. It suggests that considering the influence of spectral effects can have a substantial impact on model predictions of the wafer temperature and the temperature ramp rate. Apparently the nongray wafer, nongray window and nongray lamp behavior is more important than non-gray wall and nonopaque wafer effects.

Accurate physical properties are important for accurate predictions and the wavelength-dependent analysis can be used to help estimate the sensitivity of temperature predictions to material and radiative properties. Wavelength-dependent simulations may be used to choose the most appropriate radiation properties for diffuse-gray

analysis.

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FIGURES

Figure 1. Schematic of the reactor geometry considered for the thermal model.

Figure 2. Experimental data from Texas Instruments is used to validate the model.

Figure 3. Specific heat versus temperature for graphite and silicon.

Figure 4. Thermal conductivity versus temperature for graphite and silicon.

Figure 5. Silicon emissivity as a function of wavelength and temperature, from Sato [16].

Figure 6. Transmissivity and refractive index versus wavelength for the quartz window.

Figure 7. Transmissivity versus wavelength for the wafer at 543 and 643 K.

Figure 8. Emissivity versus wavelength for stainless steel.

Figure 9. Emissivity versus wavelength for tungsten.

Figure 10. Wafer emissivity versus temperature.

Figure 11. Comparison of temperature response at the wafer center for 6 simulations using different spectral assumptions.

Figure 12. Comparison of wafer temperature profiles at time=7 seconds for 6 simulations using different spectral assumptions.

Figure 13. Comparison of wafer temperature profiles at time=13.3 seconds for 6 simulations using different spectral assumptions.

Figure 14. Incident and emitted radiant flux at both top and bottom wafer surfaces at time=13.3 seconds.

Figure 17. Net flux at wafer center versus wavelength at time=13.3 seconds.

Figure 15. Comparison of net radiant flux at wafer surface at time=13.3 seconds for 6 simulations using different spectral assumptions.

Figure 16. Incoming flux at wafer center (top and bottom) versus wavelength at time=13.3 seconds.

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