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Modelling of an infrared halogen lamp in a rapid thermal system

P.O. Logerais [a,*], A. Bouteville [b]

[a] Université Paris-Est, Centre d'Études et de Recherche en Thermique Environnement et Systèmes (CERTES), IUT de Sénart, Avenue Pierre Point, 77127 Lieusaint, France
[b] Arts et Métiers ParisTech, LAMPA, 2 boulevard du Ronceray, BP 93525, 49035 Angers Cedex 01, France

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ABSTRACT

The heat flux distribution of an infrared halogen lamp in a Rapid Thermal Processing (RTP) equipment is studied. An overview of lamp modelling in RTP systems is given and for the first time, the infrared lamp bank is modelled by taking into consideration with accuracy a lamp portion in the bank environment. A three-dimensional (3D) lamp model, with a fine filament representation is largely presented. The model assumptions are in particular exposed with focusing on the thermal boundary conditions. The lamp temperature is calculated by solving the radiative heat transfer equation by means of the Monte-Carlo method for ray tracing. Numerical calculations are performed with the finite volume method. A very good agreement is found with experimental data in steady state. The heat amount provided by the lamp is also determined. As a first development, transient calculations are performed with the validated model and the dynamic behaviour of the lamp during heating process is determined with precision. Lastly, the model is discussed and further developments are proposed.

1. Introduction

Rapid Thermal Processes (RTP) are essential in the manufacturing of semiconductor devices such as integrated circuits, memories or solar cells. They correspond to key stages in the wafer production operations like annealing (RTA), oxidation (RTO) or Chemical Vapour Deposition (RTCVD) [1–3]. As feature size decreases towards the nanometre scale and wafer diameter increases, a deep knowledge of the phenomena involved in the processes is crucial. Indeed, there is a growing demand from rapid thermal equipment manufacturers and users to improve control, uniformity and repeatability of wafer processes. As wafer temperature requirement is especially moving to a drastic 1 K precision, wafer heating has to be mastered with high accuracy. Development of numerical tools has accompanied with success the evolution of RTP over the last two decades. Numerical tools have allowed a better understanding of the various aspects of the processes such as wafer heating, gas flow, thin film deposition, system control etc. Heat and mass transfer have been namely simulated by using the Computational Fluid Dynamics (CFD) method in an efficacious way [4,5].

In RTP systems, a silicon wafer is heated up at a very high rate by the radiative heat provided by halogen infrared lamps (Fig. 1a). Process times vary from a few seconds for implant annealing up to a few minutes for high-K annealing or curing [6]. The main technological challenge is to obtain a well controlled uniform temperature at the wafer surface. So the perfect knowledge of radiative heat emitted by the infrared lamps is necessary. The infrared lamps are usually arranged in banks in the furnace of RTP equipments (Fig. 1b). For information, in a cold wall reactor, the wafer is placed in a chamber and the wall is kept cooled by means of a water flow. A quartz window separates the chamber from the furnace. The radiative heat is transported from the lamps to the wafer through the quartz window and by reflections on the chamber wall. A controller, commonly of Proportional Integral Derivate (PID) type, connected to a pyrometer fixes the input lamp power to respect the setpoint wafer temperature.

Halogen infrared lamps consist of a tungsten filament in a middle of a quartz bulb (Fig. 1a). The latter is filled with nitrogen under around 4 bar of over pressure to reduce the tungsten filament evaporation. Halogen gases with Iodine (I), Bromine (Br), Chlorine (Cl) or Fluorine (F) are added. The created halogen cycle helps tungsten redeposition on the filament. By this method, the lamp lifetime and lamp brightness are increased. Then, the tungsten filament and the electrical power to apply can both remain stable. The lamp bases containing the connectors must be kept under 600 K. Consequently, pulsed air is flowed on the lamp bases during process.

The RTP systems were modelled in different ways. The realized models tend to be more and more accurate to best follow the trends of microelectronic manufacturing requirements.

* Corresponding author. Tel.: +33 1 64 13 46 86; fax: +33 1 64 13 45 01.
E-mail address: pierre-olivier.logerais@u-pec.fr (P.O. Logerais).

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Nomenclature

A_i	area of the patch i surface
A_λ	spectral absorptivity
A_{op}	absorptivity for an opaque surface
$A_{op,\lambda}$	spectral absorptivity for an opaque surface
A_{st}	absorptivity for a semi-transparent parallel geometry volume
$A_{st,\lambda}$	spectral absorptivity for a semi-transparent parallel geometry volume
c_p	specific heat capacity
d	radiation travelled distance
e	distance between the centres of two neighbour lamps
h_0	specific total enthalpy
i	specific internal energy function of the temperature T and the density $\boldsymbol{\rho}$
$I(r,\Omega)$	radiation intensity function of both position r and direction Ω
$I_b(r)$	intensity of blackbody radiation at the temperature of the medium
k	thermal conductivity
k_λ	spectral absorption index
L	length of the lamp
M	molar mass
M_{ij}	radiation exchange matrix (fraction of radiation emitted by patch i and absorbed by patch j)
$\vec{n}$	unit normal vector at the surface location
n_λ	spectral refractive index
$\tilde{n}_\lambda$	spectral complex refractive index
N_s	total number of patches
p	static pressure
p_0	initial pressure
P	lamp applied power
P_{atm}	atmospheric pressure
q_i	heat flux density for the patch i
Q_i	heat flux of the patch i
r	radial position
R_{op}	reflectivity for an opaque surface
$R_{op,\lambda}$	spectral reflectivity for an opaque surface
R_{st}	reflectivity for a semi-transparent parallel geometry volume
$R_{st,\lambda}$	spectral reflectivity for a semi-transparent parallel geometry volume
S_h	additional source term namely the one due to radiative transfer
$\vec{S}_M$	additional momentum source term
t	time
T	temperature
T_{fil}	filament temperature
T_j	average temperature of patch j
T_{st}	transmissivity for a semi-transparent parallel geometry volume
$T_{st,\lambda}$	spectral transmissivity for a semi-transparent parallel geometry volume
T_0	initial temperature
u, v, w	velocity components in the x, y and z directions
$\vec{V}$	velocity vector
x, y, z	Cartesian coordinates

Greek symbols

α_λ	spectral absorption coefficient
$\alpha_{\lambda,\theta}$	spectral and directional absorptivity
δ_{ij}	Kronecker delta
$\Delta\varphi_{long}$	longitudinal net exchanged heat flux between two adjacent portions
$\Delta\varphi_{1-2}$	lateral net exchanged heat flux between lamp 1 and lamp 2
κ	absorption coefficient
ε	surface emissivity
ε_j	emissivity of the patch j
ε_λ	spectral emissivity
$\varepsilon_{\lambda,\theta}$	spectral and directional emissivity
λ	radiation wavelength
ν	kinematic viscosity
Ω	propagation direction of the outgoing radiation beam
Ω'	propagation direction of the incoming radiation beam
φ_{bot}	average heat flux at the bottom of the furnace portion
$\varphi_{1\rightarrow 2}$	heat flux emitted by lamp 1 towards lamp 2
$\Phi(\Omega)$	phase function of the energy transfer from the incoming direction to the outgoing direction Ω
$\boldsymbol{\rho}$	density
ρ	surface reflectivity
σ	scattering coefficient
$\boldsymbol{\sigma}$	Stefan–Boltzmann constant (5.669×10^{-8} W m^{-2} K^{-4})
τ	transmissivity
τ_{ij}	viscous stress tensor
θ	radiation direction
θ_1	angle of incidence with the surface normal in the medium 1
θ_2	angle of refraction with the surface normal in the medium 2

Subscripts

i	patch number
j	patch number

Plévert et al. represented the lamp banks of an RTP equipment as a continuous surface emitting infrared radiation [7]. This assumption led to an overestimation of the radiation emitted since only the lamp filaments radiate.

Balakrishnan and *Edgar* used two ways for modelling lamps in the RTP equipment they considered [8]. Firstly, the relationship between the lamp power and the wafer temperature is evaluated from the heat balance of the whole system. This relationship is valid for lamps in steady state because temperature variations are low. Secondly, the wafer temperature response and the lamp power regulation system are identified as transfer functions. The dynamics of the lamps are returned by a first order model. The time constant of the lamp depends on the filament temperature T_{fil}. It is proportional to T_{fil}^{-3}.

Kersch and *Schafbauer* modelled a rapid thermal system in which measured values for the lamp power are entered in the studied RTP system model [9].

Habuka et al. studied an RTP system with circular lamps [10]. The filament lamp is modelled by source points. The DARTS method (Direct Approach using Ray Tracing Simulation) is used for ray tracing. The lamp connectors are taken into consideration in the model equations and their effect is found significant on the wafer temperature which is lower by a few percent just below them.

Chao et al. calculated view factors and approximated the radiative properties [11]. The representation of the lamps in the model is a set of concentric rings. A uniform applied power is treated. Lamps are represented in the same way in other modelling works like the one of *Park* and *Jung* [12].