STUDY OF RADIATIVE HEAT TRANSFER IN A COAXIAL CYLINDRICAL SYSTEM WITH A ROTATING POLYGONAL EMITTING PRISM

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A numerical investigation of radiative heat transfer gives the distribution of infinite effective radiation flux that falls onto the sensing element of a pyrometer over the prism-face surface as a function of the angle of face rotation.

Introduction. Measurement of the actual temperature *in situ* at different stages of thermal treatment is one of the problems of manufacture of the component base of integrated circuits.

In the majority of cases during thermal processes the objects — substrates — are moved inside the working space of a reaction chamber. Therefore, only contactless methods can be used to measure the actual surface temperature of substrates *in situ*.

To convert the signal measured by the sensing element of the pyrometer to an actual temperature, one must know the effective emissivity of the studied object ε_{ef}. The quantity ε_{ef} is a complex function depending on both the radiative and geometrical characteristics of the emitting system.

Gas-phase deposition is one of the most commonly used thermal processes in the manufacture of electronic products. The process is performed in a cooled cylindrical chamber, inside which the substrates are placed on the surface of a rotating prismatic substrate holder.

In the present paper a model of radiative heat transfer of a coaxial cylindrical system with a rotating polygonal prism is described.

To implement the model the Monte Carlo method was used [1]. This method allows the calculation of radiative heat transfer problems for systems with arbitrary geometry and different radiation characteristics (spectral and directed) of the bodies involved in mutual radiative heat transfer. It is difficult to realize this by other calculation methods.

The problem of determination of the energy of the effective radiation falling on the sensing element of the pyrometer is solved numerically. The energy of effective radiation includes the self-radiation of the substrate holder and the part of its energy reflected from the reactor walls. While the first component represents the actual temperature (of the substrate-holder surface) registered by the pyrometer, the second component being superimposed on the first, distorts the actual temperature distribution. Consequently, the sensing element of the pyrometer registers the "apparent" temperature.

Mathematical Model. In developing the model the following assumptions were made: a) the surface of the graphite substrate holder is gray and diffuse; b) the internal surface of the reaction-chamber walls has mirror reflection.

Thus, radiant-energy flux incident on the sensing element of the pyrometer can be presented as the sum of the self-radiation of the substrate-holder face Q_{ei} and the radiation mirror-reflected from the metal reactor wall and diffusely rereflected by the substrate-holder face Q_{ref}. Subsequent reflections are ignored, due to the high absorbitivity of the graphite substrate holder.

Using the method of a sphere of unit radius [1] and assuming diffusivity of the radiation of the substrate-holder faces, one can show that the portion of the self-radiation of faces does not change with substrate-holder rotation. The fact behind this assumption is that the solid angle of substrate-holder tracking from an arbitrary
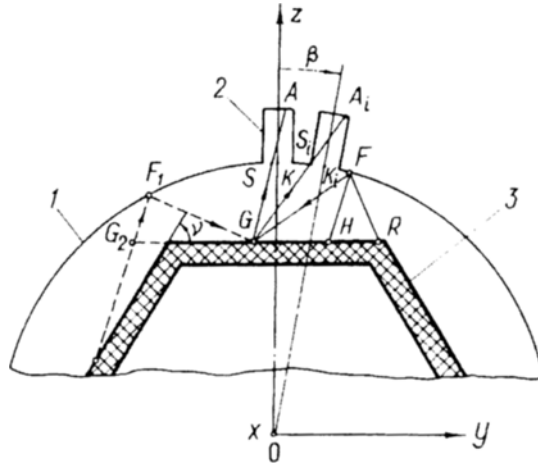

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Fig. 1. Propagation of energy beam emitted by prism face (substrate holder):
1) wall of reaction chamber; 2) working surface of sensing element; 3) prism.

point of the sensing element of the pyrometer is determined mainly by the size of the detector channel and is not related to the rotation of the substrate holder. The direct energy radiation incident on the sensing element can be calculated by the following expression

$$Q_{ei} = \varepsilon_{red}\sigma_0 \, (T_s^4 - T_{ei}^4) \, F_{ei}\varphi_{s-ei} \, .$$

The value of φ_{s-ei} is determined by the relation

$$\varphi_{s-ei} = \frac{1}{F_s} \int\limits_{F_s} d\varphi_{s-ei} dF_s \, .$$

Since $d\varphi_{s-ei}$ does not depend on the angle of substrate-holder rotation β, then φ_{s-ei} is independent of the angle β and, consequently, Q_{ei} remains constant.

The second reflected component (incident on the sensing element) of the radiation flux depends on the angle β (Fig. 1). The model presented below makes it possible to obtain the relation $Q_{ref} = f(\beta)$

The model considers the propagation of the large number of beams of energy emitted by the substrate holder. Different angular positions of the substrate holder are taken into account. To simplify the calculations, inverted motion is considered, in which the substrate holder is fixed and the radiation detector is turned through some angle β (Fig. 1).

On moving to the sensing element of the pyrometer, an energy beam emitted by the substrate holder passes through the following stages:
1) emission by face of substrate holder;
2) reflection from reaction-chamber wall;
3) incidence on face of substrate holder;
4) diffuse reflection by face of substrate holder;
5) absorption of reflected radiation by sensing element of pyrometer.

1. Emission of energy beam by substrate-holder face.

The point of emission R (Fig. 2) on a face of the substrate holder is selected arbitrarily

$$x_R = \text{Rand} \left[-\frac{b}{2} \div \frac{b}{2} \right]; \quad y_R = \text{Rand} \, | - 3b \div 3b| \, .$$

The emission of points on the substrate-holder surface with the coordinates $y > (3b)$ is ignored due to the smallness of its influence. The emission direction is determined by the azimuthal and polar angles
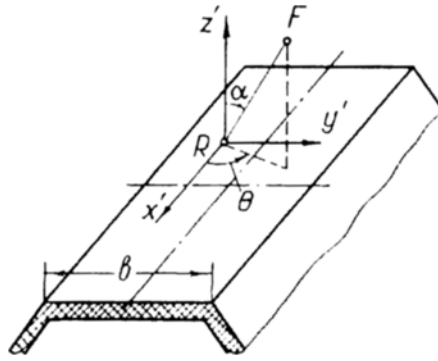
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Fig. 2. Emission of radiant energy from arbitrary point on surface of prism face.

$$\theta = \text{Rand } [-\pi \div \pi]; \quad \alpha = \arcsin \sqrt{\text{Rand } [0 \div 1]}.$$

2. Reflection from a reaction-chamber wall occurs at some point F (see Fig. 1) that has the following coordinates

$$x_F = l_{RF}(z_F - z_R)/n_{RF} + x_R, \quad y_F = m_{RF}(z_F - z_R)/n_{RF} + y_R, \quad z_F = (-B + D)/2A,$$

$$A = m_{RF} / n_{RF}^2 + 1; \quad B = 2m_{RF}(y_R - m_{RF} z_R / n_R) / n_{RF},$$

$$C = (y_R - m_{RF} z_R / n_{RF})^2 - l^2, \quad D = \sqrt{B^2 - 4AC}.$$

3. The energy beam is incident on the face of the substrate holder at an arbitrary point G with the following coordinates

$$x_G = x_H + \lambda(x_H - x_R), \quad y_G = y_H + \lambda(y_H - y_R), \quad z_G = r_n,$$

$$x_H = x_F, \quad y_H = y_F r_n / z_F, \quad \lambda = \sin(i) FH/\cos(\alpha - 2i) RH, \quad i = \arccos[(m_{RF} y_F + n_{RF} z_F) / l].$$

4. At point G on the substrate holder, the energy beam is diffusely reflected with equal intensities in all directions of the half-space.

5. The beam energy that has been diffusely reflected by point G on the substrate-holder reaches a point A on the sensing element of the pyrometer and is absorbed there.

To determine the quantity of absorbed beam energy, the coordinates of the center of the opening of the pyrometer detector (points K) are calculated. From the known coordinates of points A and G one finds the coordinates of point S. If the section $KS < r_{op}$, then the radiation from point G reaches point A of the sensing element of the pyrometer. Then the angular coefficients are calculated with allowance for the effect of the angle between the normal at point G and direction AG. Integration over the surface of the sensing element of the pyrometer makes it possible to determine the energy incident on the sensing element of the pyrometer for each angular position of the substrate holder β.

To consider the emission of neighboring faces, a similar scheme was employed in which the system of coordinates is rotated through some angle ν (Fig. 1). The coordinates of the corresponding points are

$$y_F = y_{F_1} \cos \nu + z_{F_1} \sin \nu; \quad z_F = -y_{F_1} \sin \nu + z_{F_1} \cos \nu$$

and

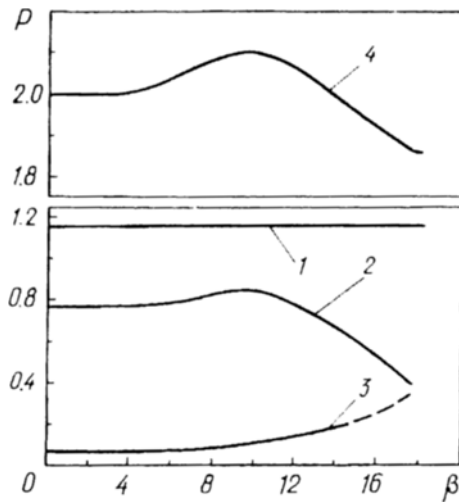$$y_{G_1} = y_{G_2} \cos \nu + z_{G_2} \sin \nu; \quad z_{G_1} = -y_{G_2} \sin \nu + z_{G_2} \cos \nu.$$

Fig. 3. Dependence of signal of sensing element of pyrometer P (a.u.) on angle of prism face rotation β (deg): 1) self-radiation of face; 2, 3) reflected radiation of the base (2) and side (3) faces; 4) resulting radiation.

Now, knowing the coordinates of points F and G, one can find the point of intersection of straight line FG with the plane of the base face of the substrate holder and obtain the coordinates of point G. Subsequent calculation is performed by the earlier formulated scheme.

The adequacy of the suggested model was verified on an experimental bench under working conditions.

A ten-face prismatic substrate holder was placed in the reaction chamber of the setup in the working position and was heated in a working gas atmosphere to a temperature of 1100-1500 K. The studied surface of the substrate holder was situated opposite the window behind which the pyrometer was placed. The PYROVAR HPH 2000 pyrometer, with an operating range of temperatures of 1073-2273 K and a range of wavelengths of $0.7 < \lambda < 1.1$ μm was aimed at the surface of the substrate holder. An N-307 plotter was used as a registering device.

Experimental part of the work is described in more detail in [2].

Results and Discussion. In processing the results, the dimensional angle of substrate-holder rotation (Fig. 1) relative to the normal to the controlled face and the dimensionless angle $\bar{\beta} = \beta / \beta_{max}$ that characterizes the ratio of the current value of the rotation angle to its maximum value were taken as determining parameters. The latter corresponds to the maximum angular position of the substrate holder within the given face.

As parameters to be determined the following were chosen: the signal P that reaches the sensing element of the pyrometer expressed in arbitrary power units; the relative signal values $\bar{P} = P / P_{max}$ that characterized the ratio of the current value of the rotation angle to its maximum value; and the ratio of the current temperature of the rotating substrate holder T_s to its maximum value $T_{s\,max}$, i.e., $\vartheta = T_s / T_{s\,max}$.

Considering the axial symmetry of the face of the substrate holder, it is expedient to present the obtained results for the half-width of the face.

Figure 3 shows the dependences of the component $1-3$ and resulting 4 signals of the sensing element of the pyrometer on the current angle of the ten-face substrate-holder rotation. It is seen from the figure that the self-radiation of the face of the substrate holder makes the greatest contribution to the resulting signal of the sensing element of the pyrometer. The value of this component is independent of the angle β. The contribution of components 2 and 3 is a complicated function of the angular position of the face. It is typical that the maximum contribution of the component of radiation reflected from the wall of the reaction chamber 3 occurs with rotation of the substrate holder through an angle close to 10°. With further rotation ($\beta > 10^{\circ}$) the value of this component markedly decreases. The contribution of the components from the neighboring faces 1 has a monotonic character, growing smoothly from the face center to its periphery.

In Fig. 4 dependences characterizing the change in the relative signal of the receiving converter of the pyrometer on the relative angle of substrate-holder rotation β are presented.
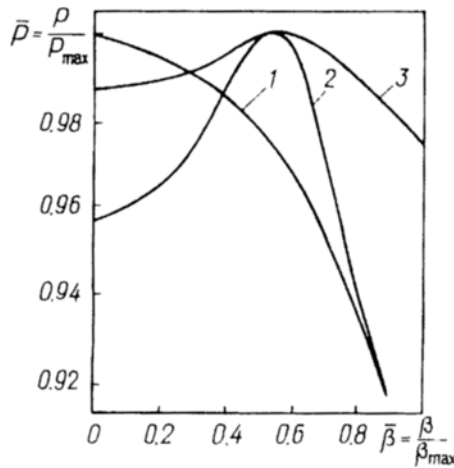
Fig. 4. Dependence of the relative value of signal of sensing element of pyrometer $(\overline{P})$ on dimensionless angle of substrate-holder rotation $(\overline{\beta})$ for various diameters of reaction chamber $(D_{r.ch.})$: 1) $D_{r.ch.} = 0.36$ m; 2) $D_{r.cj.} = 0.28$ m, calculation according to the model; 3) $D_{r.ch.} = 0.28$ m, experimental data.

An analysis of curves 2 and 3 obtained for similar conditions shows a satisfactory agreement between them. Namely, a smooth rise from the face center $(\overline{\beta} = 0)$, attainment of P_{max} when $\overline{\beta} \approx 0.55$, and reduction of P when $\overline{\beta} > 0.55$. P has its minimum on the edge of the substrate-holder face.

The more distinct shape of curve 2 is, apparently, due to the mirror character of reflection from the walls of the reaction chamber adopted in the model. In fact, due to precipitation of reaction products on the walls of the reaction chamber the character of reflection becomes diffuse. This assumption can probably explain the smoother variation of curve 3.

A change in the geometry of the reaction chamber, i.e., an increase in its diameter of from 0.28 to 0.36 m with preservation of the dimensions and shape of the substrate holder, leads to a substantial change in the character of curve 1. It can be assumed with a certain probability that in this case the character of the components reflected from the walls of the reaction chamber changes greatly, thus changing the resulting signal of the receiving converter of the pyrometer.

Conclusions.

1. A mathematical model of radiative heat transfer in a coaxial cylindrical system with a polygonal rotating prismatic substrate holder is developed.

2. The main contribution to the resulting signal of the sensing element of the pyrometer is made by the self-radiation of the substrate holder, which does not depend on the angle of its face rotation.

3. Reflected components greatly change with a change in the geometry of the reaction chamber.

4. As the substrate holder approaches the reflecting walls of the reaction chamber, the character of the resulting pyrometer signal changes.

NOTATION

b, face width; β, angle of prism rotation relative to the normal to its face; l, inner radius of cylinder; F, area; P, dimensional value of sensing-element signal; Q, radiation flux; r_n, radius of the circle inscribed in an n-gonal prism; T, temperature; α, polar angle; φ, slope; ε, emissivity; λ, relative distance; ν, angle of rotation of the coordinate system; σ_0, Stefan-Boltzmann constant; θ, azimuth angle; x, y, z, coordinates of points on face surface; R and $|v...w|$, random number with uniform distribution within the range $|v...w|$; $l_{RF} = \cos\theta \sin\alpha$; $m_{RF} = \sin\theta \sin a$; $n_{RF} = \cos\alpha$, cosines of direction angles; $\overline{P} = P/P_{max}$, relative current value of sensing-element signal; $\vartheta = T_s/T_{s\,max}$, relative current value of temperature of prism face; A, F, G, H, K, R, S, points on the surfaces of

the face, reaction-chamber wall, window, and sensing element (see Fig. 1). Subscripts: ef, effective; ei, eigenvalue; s, surface of prism (substrate holder); ref, reflection; op, opening; el, sensing element; red, reduced value.

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