LITERATURE CITED

1. Yu. A. Zagromov and M. D. Kats, "Calculation of thermophysical characteristics of coatings deposited on a metal base by the pulsed method," Dep. VINITI, 09/-03/87, No. 1686-V87.
2. R. D. Cowan, J. Appl. Phys., 32, No. 7, 1363-1370 (1961).
3. R. D. Cowan, J. Appl. Phys., 34, No. 4, 926-927 (1963).
4. V. I. Chistyakov, Teplofiz. Vys. Temp., 11, No. 4, 832-837 (1973).

OPTIMIZATION OF THE CONSTRUCTION OF THE REACTION CHAMBER ON TEMPERATURE DISTRIBUTION IN A SEMICONDUCTOR PLATE ON HEATING BY INCOHERENT RADIATION

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Irradiation and temperature fields are calculated in a semiconductor plate heated by pulsed incoherent radiation. An optimal arrangement of the sample and irradiation elements is selected.

Increasing application of pulsed thermal processing of semiconductor structures by incoherent radiation in the technology of solid-state electronics calls for constant improvement in the processing equipment. The reliability of operation, the percentage of the output of suitable semiconductor devices, is determined in many respects by the uniformity in the temperature distribution along the plate during thermal operations, in particular, when heated by pulsed incoherent radiation.

The choice of the construction of the reaction chamber, which determines the distribution of temperature fields along the processed plate, is considered in [1, 2]. However, at present there are no models of reaction chambers that incorporate a direct dependence of the temperature distribution on the arrangement of the reactor elements. Available models for calculating temperature fields under condition of a homogeneous irradiation [3, 5] neglect dynamic and nonlinear effects, which cannot affect the temperature distribution.

The purpose of the present paper is to find an optimal arrangement of the plate and radiation elements in order to provide the minimal temperature gradient in the plate.

To solve the formulated problem a mathematical model of the temperature distribution along the radius of the semiconductor plate is developed, which allows for the dynamics of heating and also for nonlinear optical and thermophysical characteristics of the semiconductor sample. In addition, the model allows for the following features: plate dimensions; distances from the plate to the plane of the location of the lamps and to the chamber's walls; one-sided or two-sided heating; sizes, powers, and types of heating lamps; their number and arrangement; and the reflection coefficient of the chamber's walls.

We consider assumptions that can be made when solving the formulated problem. As is shown in [5], when the duration of the processing pulse is of the order of a few seconds, the temperature difference of the face and reverse sides of the plate is equal to tenths of a percent. Therefore, with a sufficient degree of accuracy we can average the temperature along the thickness of the sample and assume that it is constant.

We consider the reaction chamber represented in Fig. 1, in which the semiconductor plate is heated from one side or two sides. In the chamber, the sample is placed vertically in order to decrease the sagging of the large-diameter plate during high-temperature processing.

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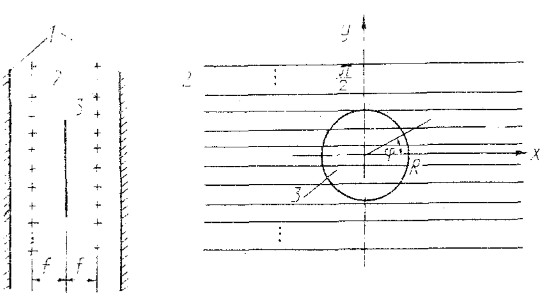

Fig. 1. A basic diagram of the reaction chamber: 1) reflectors, 2) radiator, 3) plate.

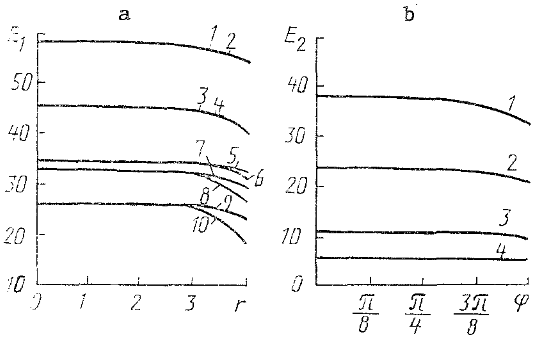

Fig. 2. The irradiation distribution for the face side (a) and the butt end (b) of the plate for the case of one-sided heating: 1) $n = 18$, $\varphi = 0$, $f = 1 \times 10^{-2}$ m; 2) $n = 18$; $\varphi = \pi/2$, $f = 1 \times 10^{-2}$ m; 3) $n = 18$, $\varphi = 0$, $f = 3 \times 10^{-2}$ m; 4) $n = 18$, $\varphi = \pi/2$, $f = 3 \times 10^{-2}$; 5) $n = 18$, $\varphi = 0$, $f = 5 \times 10^{-2}$ m; 6) $n = 18$, $\varphi = \pi/2$, $f = 5 \times 10^{-2}$ m; 7) $n = 15$, $\varphi = 0$, $f = 5 \times 10^{-2}$ m; 8) $n = 15$, $\varphi = \pi/2$, $f = 5 \times 10^{-2}$ m; 9) $n = 12$, $\varphi = 0$, $f = 5 \times 10^{-2}$ m; 10) $n = 12$, $\varphi = \pi/2$, $f = 5 \times 10^{-2}$ m. E_1, E_2) 10^4 W/m^2; r) 10^{-2} m; φ) rad.

The irradiation was calculated as follows. The density of the incident flow at a point ξ on the surface was calculated as a sum of flow densities created by the real and imaginary radiation sources formed by the reflection from the chamber's walls and the plate itself.

$$E_s(\xi) = \sum_{i=1}^{m+1} \sum_{j=1}^{n} k_{ij} e_{ij}, \quad s = 1,\ 2. \tag{1}$$

The number of reflections m from the reflectors was selected by the principle given in [2]. The radiation from each lamp e_{ij} was determined from expressions obtained from the lamp e_{ij} was determined from expressions obtained from the laws of photometry.

The experimental results show that for a sufficiently close arrangement of the radiator and the plate and also for a lamp length exceeding the plate diameter, we cannot ignore the irradiation of the butt end as was done, for example, in [2]. Therefore, calculations allowed for the irradiation of both the face (reverse) side and the butt end of the semiconductor plate.

The irradiation of the face (reverse) side E_1, for which the vector of the normal was perpendicular to the plane of the location of the lamps, was calculated from (1) for

$$e_{ij} = \frac{P f_i}{4\pi L \left[f_i^2 + (y_j - r\sin\varphi)^2\right]} \left\{ \frac{x_e^i - r\cos\varphi}{\left[(x_e^i - r\cos\varphi)^2 + f_i^2 + (r\sin\varphi - y_j)^2\right]^{1/2}} - \frac{x_s^i - r\cos\varphi}{\left[(x_s^i - r\cos\varphi)^2 + f_i^2 + (y_j - r\sin\varphi)^2\right]^{1/2}} \right\}.$$

The irradiation of the butt end E_2 was calculated similarly, however, in the derivation of the expression for calculating e_{ij} we took into account that the vector of the normal to the butt end of the plate was parallel to the plane of the radiator:

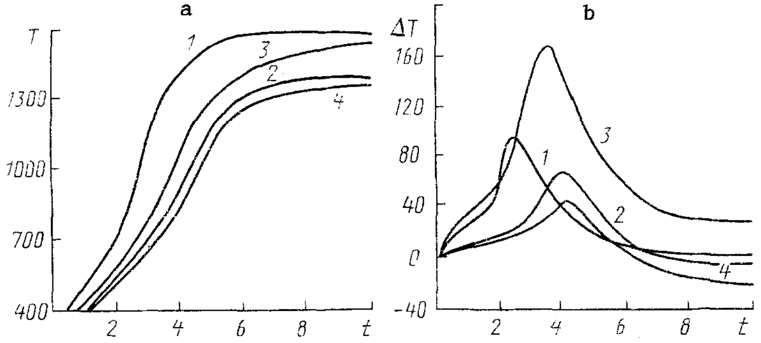

Fig. 3. The temperature change in the center of the plate (a) and temperature differences between the rim and the center (b) during heating: 1) $f = 5 \times 10^{-2}$ m, two-sided heating; 2) $f = 3 \times 10^{-2}$ m, one-sided heating; 3) $f = 2 \times 10^{-2}$ m, one-sided heating; 4) $f = 4 \times 10^{-2}$ m, one-sided heating. T) K; t) sec.

$$e_{ij} = \frac{P}{4\pi L}\left\{\cos\varphi\left[\frac{1}{[(x_s^i - R\cos\varphi)^2 + (y_j - R\sin\varphi)^2 + f_i^2]^{1/2}} - \frac{1}{[(x_e^i - R\cos\varphi)^2 + (y_j - R\sin\varphi)^2 + f_i^2]^{1/2}}\right] + \frac{(y_j - R\sin\varphi)\sin\varphi}{[(y_j - R\sin\varphi)^2 + f_i^2]^{1/2}}\left[\frac{x_e^i - R\cos\varphi}{[(x_e^i - R\cos\varphi)^2 + (y_j - R\sin\varphi)^2 + f_i^2]^{1/2}} - \frac{x_s^i - R\cos\varphi}{[(x_s^i - R\cos\varphi)^2 + f_i^2 + (y_j - R\sin\varphi)^2]^{1/2}}\right]\right\}.$$

As a sample we selected a silicon plate 7.6×10^{-2} m in diameter and 3.8×10^{-4} m in thickness, and as radiation sources, type KG-220-1500 halogen incandescent lamps.

In Fig. 2a, the calculated dependencies of the irradiation of the face side along the plate radius are given for two directions ($\varphi = 0$, $\varphi = \pi/2$) for different numbers of lamps and for different values of f. Calculations were performed for the case of one-sided heating under the condition that the distance from the plate to the lower wall was large enough to not affect considerably the irradiation distribution.

As is seen, even for $f = 5 \times 10^{-2}$ m for the number of lamps equal to 15 and for the distance between them equal to 1×10^{-2} m the difference in irradiation at points (R, 0) and (R, $\pi/2$) is 6%. When the number of lamps increases to 18, even at $f = 1 \times 10^{-2}$ m, a practically homogeneous irradiation of the sample area is attained.

In Fig. 2b, the irradiation distribution for the butt end of the plate is shown for the angle of rotation φ for different values of f for a fixed number of lamps equal to 18. It is seen that the irradiation of the butt end of the plate can be considered as practically homogeneous for $f \leq 2 \times 10^{-2}$ m.

For the case of two-sided heating, radiators are located symmetrically with respect to the plate; therefore, the irradiation values shown in Fig. 2 are doubled.

Analysis of the given data allows us to assume that irradiation of the plate by eighteen lamps for $f \leq 2 \times 10^{-2}$ m can be treated as axisymmetric: therefore, the distribution of temperature fields can be described by a one-dimensional equation of the form

$$\rho C(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} rK(T)\frac{\partial T}{\partial r} + S(r, T) \tag{2}$$

with the initial condition

$$T(r, 0) = T_0 \tag{3}$$

and boundary conditions

$$q_0 \equiv \frac{\partial T(0,\ t)}{\partial r} = 0, \tag{4a}$$

$$q_N \equiv -K(T)\frac{\partial T(R,\ t)}{\partial r} = e\sigma[T^4(R,\ t) - T_0^4] + \alpha_e[T(R,\ t) - T_c] - E_2. \tag{4b}$$

The function of the internal sources is of the form

$$S(r,\ T) = \frac{1}{d}\{E_1 a_t(T) - 2e\sigma(T^4(r) - T_0^4) - 2\alpha_e[T(r) - T_c]\}.$$

The value $a_t(T)$ represents an integral absorption capacity of the semiconductor plate and is determined as

$$a_t(T) = \frac{\int\limits_0^\infty [1 - R_s(\lambda)][1 - \exp(-\alpha_s(\lambda,\ T)d)]I(\lambda)\,d\lambda}{\int\limits_0^\infty I(\lambda)\,d\lambda}.$$

Problem (2)-(4) was solved numerically in the following manner. In the region (0, R), (0, Q), we introduced the grid $\omega_{h\tau} = \{(r_i,\ t r_j),\ h_i = r_i - r_{i-1},\ i = 0,\ 1,\ \ldots,\ N,\ r_0 = 0,\ r_N = R;\ t_j = j\tau,\ j = 0,\ 1,\ \ldots,\ M,\ t_0 = 0,\ t_M = Q\}$ and considered on it a difference scheme

$$\frac{\rho C_i^{j-1/2}}{\tau}(T_i^j - T_i^{j-1}) = \frac{\gamma}{r_i^*}(q_{i-1/2}^j - q_{i+1/2}^j) + \frac{1-\gamma}{r_i^*}(q_{i-1/2}^{j-1} - q_{i+1/2}^{j-1}) + S_i^{j-1/2}, \tag{5}$$

$$q_{i-1/2}^j = r_{i-1/2}K_{i-1/2}^j\left(\frac{T_i^j - T_{i-1}^j}{h_i}\right),\ r_i^* = \frac{r_{i+1} + r_i}{2},\ i = 1,\ 2,\ \ldots,\ N-1, \tag{6}$$

$$T_i^0 = T_0,\ i = 0,\ 1,\ \ldots,\ N,$$

approximating (2) and (3), respectively. The finite-difference approximation of conditions (4) was obtained in a similar way:

$$\frac{\rho C_0^{j-1/2}}{\tau}(T_0^j - T_0^{j-1}) = \frac{\gamma}{r_0^*}(q_0^j - q_{1/2}^j) + \frac{1-\gamma}{r_0^*}(q_0^{j-1} - q_{1/2}^{j-1}) + S_0^{j-1/2}, \tag{7}$$

$$\frac{\rho C_N^{j-1/2}}{\tau}(T_N^j - T_N^{j-1}) = \frac{\gamma}{r_N^*}(q_{N-1/2}^j - q_N^j) + \frac{1-\gamma}{r_N^*}(q_{N-1/2}^{j-1} - q_N^{j-1}) + S_N^{j-1/2}, \tag{8}$$

$$r_0^* = \frac{r_1}{2},\ r_N^* = \frac{R + r_{N-1}}{2},\ j = 1,\ 2,\ \ldots,\ M.$$

Since Eq. (2) is nonlinear, an iteration process was used for its solution. The temperature in the jth time layer for the lth iteration was determined from the solution of the system of linear algebraic equations of the form

$$\begin{gathered} -c_0^{l-1}(T_0^j)^l + b_0^{l-1}(T_1^j)^l = -p_0^{l-1},\ a_i^{l-1}(T_{i-1}^j)^l - c_i^{l-1}(T_i^j)^l + \\ \vdots \\ + b_i^{l-1}(T_{i+1}^j)^l = -p_i^{l-1},\ a_N^{l-1}(T^j)_{N-1}^l - c_N^{l-1}(T_N^j)^l = -p_N^{l-1}. \\ \vdots \end{gathered} \tag{9}$$

The coefficients a_i^{l-1}, b_i^{l-1}, c_i^{l-1}, p_i^{l-1} ($i = 0,\ 1,\ \ldots,\ N$) were obtained after arranging like terms in Eqs. (5), (7), and (8).

The system of equations (9) was solved by a pivotal method [6]. The iteration process was completed when condition

$$\|(T^j)^l - (T^j)^{l+1}\| < \varepsilon$$

was satisfied.

In Fig. 3a, the calculated curves for the heating of the center of a homogeneous silicon plate with the concentration of charge carriers equal to 10^{15} cm^{-3} for different f are represented, and in Fig. 3b, the time dependence of the temperature difference ΔT is shown between the point with $r = R$ and the point with $r = 0$. It is seen from Fig. 3 that ΔT increases during heating reaching a maximal value, after which it diminishes sharply. When a steady-state regime is reached, the temperature difference between the rim and the center also assumes a constant value. Such a form of the dependence of ΔT on t is due to the fact that at the beginning of heating the luminous flux incident on the butt end of the plate exceeds the flux radiated by this part of the surface. When the temperature increases, losses due to convection and radiation increase, and ΔT decreases.

It can be noted that the maximum in the temperature difference for each heating curve is at a temperature of the order of 850 K in the center of the plate. This is explained by the fact that near this temperature the integral absorption capacity of silicon changes sharply because of the intense absorption of infrared radiation by free charge carriers. For the same reason, all the curves shown in Fig. 3a exhibit an increase in the heating rate at 850 K.

An experimental measurement of the absolute temperature and the temperature difference between the rim of the plate (at a point at a distance 2×10^{-3} from the butt end) and the center conducted with the help of two chromel-alumel thermocouples has shown good agreement with the calculated data.

Based on the conducted calculations we can draw the following conclusions. When the distance between the lamps is 1×10^{-2} m the gradient of the plate irradiation with respect to the angle φ tends to zero for the number of lamps equal to 18. The selection of the optimal distance from the plate to the radiator allows one to minimize the temperature gradient with respect to the radius of the plate for both one-sided and two-sided heating either in a steady-state regime or in a dynamic regime. A strong dependence of the absorption capacity of the silicon with the given concentration of the charge carriers results in considerable radial temperature differences during a transient process. These temperature gradients can be removed by using irradiation of the sample depending both on the coordinate and time.

NOTATION

Here $E(\xi)$ is irradiation at point ξ; k_{ij}, reduced reflection coefficient; e_{ij}, irradiation from the jth lamp and the ith radiator; m, the number of imaginary radiators; n, the number of lamps in the radiator; P, the power of a lamp; f, the distance from the plate to the radiator; L the length of a lamp; x_j^e, x_j^s, coordinates of the end and the start of the part of the lamp visible at point ξ; φ, r, coordinates of the point ξ on the plate; r, radius of the plate; ρ, silicon density; T, temperature; $C(T)$, $K(T)$, coefficients of specific heat capacity and heat conduction of silicon; T_0, plate temperature before processing; $S(r, T)$, function of the heat source; e, emission coefficient of silicon; σ, Stefan—Boltzmann constant; α^c, coefficient of convective exchange; E_1, E_2, irradiation of the face surface and the butt end of the plate; T_c, ambient temperature; $\alpha_t(T)$, integral absorption capacity of a silicon plate; λ, wavelength; $R_s(\lambda)$, the reflection coefficient of silicon; $\alpha_s(\lambda, T)$, the absorption coefficient of silicon; $I(\lambda)$, radiator spectrum; t, time coordinate.

LITERATURE CITED

1. D. E. Zvorykin and Yu. I. Prokhorov, Application of Infrared Heating in the Electronics Industry [in Russian], Moscow (1980).
2. Yu. P. Sin'kov, Élektron. Tekh., Series 1, No. 3 (363), 36-41 (1984).
3. G. Bentini, L. Correra, and C. Donolato, J. Appl. Phys., 56, No. 10, 2922-2929 (1984).
4. N. N. Naumenko, I. L. Prokhorenko, V. D. Shimanovich, et al., Radiotekh. Élektron., No. 15, 113-118 (1986).
5. V. S. Kulikov, M. N. Rolin, and N. L. Yadrevskaya, Fiz. Khim. Obrab. Mater., No. 2, 41-44 (1989).
6. A. A. Samarskii, Theory of Difference Schemes [in Russian], Moscow (1983).