About Controlling of Regimes of Heating During Growth a Heterostructures from Gas Phase

E.L. Pankratov^{1,*}, E.A. Bulaeva²

¹Nizhny Novgorod State University, 23 Gagarin avenue, Nizhny Novgorod, 603950, Russia

²Nizhny Novgorod State University of Architecture and Civil Engineering, 65 Il'insky Street, Nizhny Novgorod, 603950, Russia

*Corresponding Author: elp2004@mail.ru

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Abstract In this paper we analyzed distribution of temperature in a reactor for epitaxial growth from gaze phase. Based on the analysis it has been formulated recommendations to increase homogeneity of distribution of temperature in depth of heterostructure, which has been grown in the reactor.

Keywords Gas Phase Epitaxy; Analytical Approach To Model of Epitaxy Process; Optimization of Epitaxy Process

1. Introduction

In the present time most part of the solid state electronic devices are manufacturing based on heterostructures [1-10]. It could be used different methods to growth heterostructures: molecular-beam epitaxy, epitaxy from gas phase, magnetron sputtering [1,6]. One of problems of manufacturing of heterostructures is growth of the epitaxial layers with larger homogeneity of their properties. In this paper we consider an approach to increase the homogeneity of the properties during growth of heterostructures from gas phase. To illustrate the approach we consider a vertical reactor for epitaxy from gas phase (see Fig. 1). In the composition of the reactor it has been used keeper of substrate. A substrate could be fixed on the keeper and revolves with angular velocity ω . A spiral presents around the keeper of substrate. Let us consider an electrical current in the spiral. This current gives us possibility to heat the keeper of substrate and the substrate due to electro-magnetic irradiation and scin-effect. Some materials in gas form for growth required heterostructure are inserting from the substrate in admixture with a gas-carrier. Let us consider an external casing to decrease losing of the above materials in gas phase (gases-reagents) and the gas-carrier from outside of the device. The above heating, which has been induced by electrical current in spiral, is necessary for activation of chemical reaction between materials in gas form, which are used for growth of epitaxial layers of heterostructure. It is practicably to use such regime of epitaxial growth, which corresponds to maximal increasing of homogeneity of temperature in depth of heterostructure. Using the regime attracted an interest to increase homogeneity of properties of layers of heterostructures. Main aim of the present paper is determination of conditions of growth of above heterostructure, which give us possibility to increase homogeneity of properties of the structure.

Figure 1. A plant for the gas phase epitaxy in neighborhoods of reaction zone

2. Method of Solution

To solve our aims we determine spatio-temporal distribution of temperature. We determined the required distribution of temperature by solving the following boundary problem [11]

$$c(T) \frac{\partial T(\vec{r}, t)}{\partial t} = \text{div} \{ \lambda \cdot \text{grad} [T(\vec{r}, t)] - \vec{v}(\vec{r}, t) \cdot c(T) \cdot T(\vec{r}, t) \cdot C(\vec{r}, t) \} + p(\vec{r}, t), \quad (1)$$

where $\vec{v}$ is the speed of flow of mixture of gases; $\vec{r} = \vec{r}(r, \varphi, z)$ - is the radius-vector in spherical system of coordinate; $c(T)$ is the heat capacitance; $T(\vec{r}, t)$ is the spatio-temporal distribution of temperature; $p(\vec{r}, t)$ is the density of heat power, which has been generated in the system keeper of substrate – substrate; r, φ, z and t are the current cylindrical coordinates and time, respectively; $C(\vec{r}, t)$ is the spatio-temporal distribution of concentration of mixture of gases. The first term of the Eq. (1) describes diffusion of gas from beginning of reactor ($z=-L$) to end of the reactor ($z=L$). The second term of the Eq. (1) describes convection trans-port of gas with velocity of flow $\vec{v}$ under influence of external pressure P .

To solve this boundary problem it is necessary to take into account stream of mixture of gases and concentration of the mixture. Let us determine the required values by solving the equation of Navier-Stokes and the second Fourier law. We also assume that radius of keeper of substrate R essentially larger, than thickness of diffusion and near-boundary layers. We also assume, that stream of gas is laminar. In this situation the appropriate equations could be written as

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} = -\nabla \left(\frac{P}{\rho} \right) + \nu \Delta \vec{v}, \quad (2)$$

$$\frac{\partial C(\vec{r}, t)}{\partial t} = \text{div} \{ D \cdot \text{grad} [C(\vec{r}, t)] - \vec{v}(\vec{r}, t) \cdot C(\vec{r}, t) \}, \quad (3)$$

where D is the diffusion coefficient of mixture of gases (gases-reagents and gas- carrier); P is the pressure; ρ is the density of gases; ν is the kinematical viscosity. Let us consider the regime of the limiting flow, when all forthcoming to the disk molecules of deposit material are depositing on the substrate, flow is homogenous and one dimension. In this case boundary and initial conditions could be written as

$$\begin{aligned} C(r, \varphi, -L, t) &= C_0(t), C(r, \varphi, 0, t) = 0, C(r, 0, z, t) = C(r, 2\pi, z, t), C(r, \varphi, z, 0) = C_0(t) \delta(z+L), \\ C(0, \varphi, z, t) &\neq \infty, \left. \frac{\partial C(\vec{r}, t)}{\partial r} \right|_{r=R} = 0, \left. \frac{\partial C(\vec{r}, t)}{\partial \phi} \right|_{\phi=0} = \left. \frac{\partial C(\vec{r}, t)}{\partial \phi} \right|_{\phi=2\pi}, \left. \frac{\partial T(\vec{r}, t)}{\partial \phi} \right|_{\phi=0} = \left. \frac{\partial T(\vec{r}, t)}{\partial \phi} \right|_{\phi=2\pi}, \\ -\lambda \left. \frac{\partial T(\vec{r}, t)}{\partial r} \right|_{r=R} &= \sigma T^4(R, \phi, z, t), -\lambda \left. \frac{\partial T(\vec{r}, t)}{\partial z} \right|_{z=-L} = \sigma T^4(r, \phi, -L, t), T(r, \varphi, z, 0) = T_r \\ \left. \frac{\partial v_r(\vec{r}, t)}{\partial r} \right|_{r=0} &= \left. \frac{\partial v_r(\vec{r}, t)}{\partial r} \right|_{r=R}, \left. \frac{\partial v_\phi(\vec{r}, t)}{\partial \phi} \right|_{\phi=0} = \left. \frac{\partial v_\phi(\vec{r}, t)}{\partial \phi} \right|_{\phi=2\pi}, T(r, 0, z, t) = T(r, 2\pi, z, t), \\ \left. \frac{\partial v_r(\vec{r}, t)}{\partial r} \right|_{r=0} &= \left. \frac{\partial v_r(\vec{r}, t)}{\partial r} \right|_{r=R}, \left. \frac{\partial v_\phi(\vec{r}, t)}{\partial \phi} \right|_{\phi=0} = \left. \frac{\partial v_\phi(\vec{r}, t)}{\partial \phi} \right|_{\phi=2\pi}, v_\phi(r, \varphi, z, 0) = 0, v_z(r, \varphi, -L, 0) = V_0 \quad (4) \\ -\lambda \left. \frac{\partial T(\vec{r}, t)}{\partial z} \right|_{z=L} &= \sigma T^4(r, \phi, L, t), T(0, \varphi, z, t) \neq \infty, v_r(r, \varphi, -L, t) = 0, v_r(r, \varphi, 0, t) = 0, \\ v_r(r, \varphi, L, t) &= 0, T(r, \varphi, z, 0) = T_r, v_r(r, 0, z, t) = v_r(r, 2\pi, z, t), v_r(0, \varphi, z, t) \neq \infty, v_\phi(r, \varphi, 0, t) = \omega r, \\ v_\phi(r, \varphi, -L, t) &= 0, v_\phi(r, \varphi, L, t) = 0, v_\phi(r, 0, z, t) = v_\phi(r, 2\pi, z, t), v_\phi(0, \varphi, z, t) \neq \infty, v_z(r, \varphi, -L, t) = V_0, \\ v_z(r, \varphi, 0, t) &= 0, v_z(r, \varphi, L, t) = 0, v_z(r, 0, z, t) = v_z(r, 2\pi, z, t), v_z(0, \varphi, z, t) \neq \infty, v_r(r, \varphi, z, 0) = 0, \end{aligned}$$

where $\sigma = 5,67 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$, T_r is the room temperature. The conditions describe absents of gas flow through casing of reactor at $r=R$, absence of infinite increasing of approximation of concentration of gas at $r=0$, conditions of periodicity of concentration of gas with varying of angular coordinate φ , initial condition and condition at $z = -L$ correspond to presents of

concentration of gas on beginning of reactor in initial moment of time, reason of considered value of concentration in the end of reaction $z = L$ is necessity to decrease energy cost during growth of heterostructure.

Equations for components of velocity of flow with account cylindrical system of coordinate could be written as

$$\left\{ \begin{aligned} \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\phi}{r} \frac{\partial v_\phi}{\partial \phi} + v_z \frac{\partial v_z}{\partial z} &= v \left(\frac{\partial^2 v_r}{\partial r^2} + \frac{\partial^2 v_r}{\partial r \partial z} - \frac{\partial^2 v_r}{\partial z^2} + \frac{\partial^2 v_z}{\partial r \partial z} \right) - \frac{\partial}{\partial r} \left(\frac{P}{\rho} \right) \\ \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\phi}{r} \frac{\partial v_\phi}{\partial \phi} + v_z \frac{\partial v_z}{\partial z} &= \\ &= v \left(\frac{1}{r} \frac{\partial^2 v_r}{\partial r \partial \phi} + \frac{2}{r^2} \frac{\partial^2 v_\phi}{\partial \phi^2} - \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \phi \partial z} + \frac{\partial^2 v_\phi}{\partial z^2} \right) - \frac{1}{r} \frac{\partial}{\partial \phi} \left(\frac{P}{\rho} \right), \\ \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\phi}{r} \frac{\partial v_\phi}{\partial \phi} + v_z \frac{\partial v_z}{\partial z} &= v \left(\frac{\partial^2 v_r}{\partial z^2} + \frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \phi^2} \right) - \frac{\partial}{\partial z} \left(\frac{P}{\rho} \right) \end{aligned} \right. \quad (5)$$

Let us transform the system of Eqs.(5) to integro-differential form to simplify solution of them. The integro-differential equations are presented in the Appendix.

We determine solution of the system of equations by using method of averaging of function corrections [12-15]. Framework the approach we replace components of velocity of flow v_r , v_ϕ and v_z on their average values α_{1r} , $\alpha_{1\phi}$ and α_{1z} , i.e. $v_r \rightarrow \alpha_{1r}$, $v_\phi \rightarrow \alpha_{1\phi}$, $v_z \rightarrow \alpha_{1z}$ in right sides of the integro-differential equations. After this replacement we obtained the first-order approximations of components of velocity. The approximations are presented in the Appendix. We determine the average values α_{1r} , $\alpha_{1\phi}$ and α_{1z} by the standard relations [12-15]

$$\alpha_{1r} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L v_{1r} dz d\phi dr dt, \quad \alpha_{1\phi} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L v_{1\phi} dz d\phi dr dt, \\ \alpha_{1z} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L v_{1z} dz d\phi dr dt, \quad (6)$$

where Θ is the continuance of stream of mixture of gases. Substitution of the above first- order approximations into the relations (6) and insignificant transformations give us possibility to obtain equations for the required average values α_{1r} , $\alpha_{1\phi}$ and α_{1z} in the following form

$$\left\{ \begin{aligned} a_1 \alpha_{1r}^2 + a_2 \alpha_{1\phi}^2 + a_3 \alpha_{1z}^2 + a_4 \alpha_{1r} &= a_5 \\ b_1 \alpha_{1r}^2 + b_2 \alpha_{1\phi}^2 + b_3 \alpha_{1z}^2 + b_4 \alpha_{1r} + b_5 \alpha_{1\phi} &= b_6 \\ c_1 \alpha_{1r}^2 + c_2 \alpha_{1\phi}^2 + c_3 \alpha_{1z}^2 + c_4 \alpha_{1r} + c_5 \alpha_{1z} &= c_6 \end{aligned} \right. \quad (7)$$

System of equations (7) could be solved by standard approaches [16]. Values of parameters a_i , b_i and c_i are presented in the Appendix.

The second-order approximations of components of velocity of flow could be obtained by replacement of the required functions in right sides of integro-differential forms of Eqs.(5) on the following sums $v_r \rightarrow \alpha_{2r} + v_{1r}$, $v_\phi \rightarrow \alpha_{2\phi} + v_{1\phi}$ and $v_z \rightarrow \alpha_{2z} + v_{1z}$. The approximations are presented in the Appendix. We calculated the average values α_{2r} , $\alpha_{2\phi}$ and α_{2z} by the standard relations [12-15]

$$\alpha_{2r} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L (v_{2r} - v_{1r}) dz d\phi dr dt, \quad \alpha_{2\phi} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L (v_{2\phi} - v_{1\phi}) dz d\phi dr dt, \\ \alpha_{2z} = \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L (v_{2z} - v_{1z}) dz d\phi dr dt. \quad (8)$$

Substitution of the first- and the second-order approximations into relations (8) gives us possibility to obtain equations for required average values

$$\begin{cases} A_1\alpha_{2r}^2 + A_2\alpha_{2\phi}^2 + A_3\alpha_{2z}^2 + A_4\alpha_{2r} + A_5\alpha_{2\phi} + A_6\alpha_{2z} = A_7 \\ B_1\alpha_{2r}^2 + B_2\alpha_{2\phi}^2 + B_3\alpha_{2z}^2 + B_4\alpha_{2r} + B_5\alpha_{2\phi} + B_6\alpha_{2z} = B_7 \\ C_1\alpha_{1r}^2 + C_2\alpha_{1\phi}^2 + C_3\alpha_{1z}^2 + C_4\alpha_{1r} + C_5\alpha_{1\phi} + C_6\alpha_{1z} = C_7, \end{cases} \quad (9)$$

Solution of the equations could be obtain by standard approaches [16]. Values of parameters A_i , B_i and C_i are presented in the Appendix.

In this section we obtained components of velocity of flow of mixture of materials in gas phase, which are used for growth of heterostructure, and gas-carrier in the second-order approximation framework method of averaging of function corrections. Usually the second-order approximation is enough good approximation to make qualitative analysis of obtained solution and to obtain some quantitative results [13-15].

Let us rewrite Eqs.(1) and (3) by using cylindrical system of coordinate. In this situation we assume, that heat conduction coefficient and heat capacitance weakly dependent on temperature and one can neglect by the dependence. In this situation the equation could be written as

$$\begin{aligned} c \frac{\partial T(\vec{r}, t)}{\partial t} = & \lambda \frac{\partial^2 T(\vec{r}, t)}{\partial r^2} + \lambda \frac{1}{r^2} \frac{\partial^2 T(\vec{r}, t)}{\partial \phi^2} + \lambda \frac{\partial^2 T(\vec{r}, t)}{\partial z^2} - c \cdot \frac{\partial}{\partial r} [v_r(\vec{r}, t) \cdot C(\vec{r}, t) \cdot T(\vec{r}, t)] - \\ & - \frac{c}{r} \frac{\partial}{\partial \phi} [v_\phi(\vec{r}, t) \cdot C(\vec{r}, t) \cdot T(\vec{r}, t)] - c \cdot \frac{\partial}{\partial z} [v_z(\vec{r}, t) \cdot C(\vec{r}, t) \cdot T(\vec{r}, t)] + p(\vec{r}, t), \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{\partial C(\vec{r}, t)}{\partial t} = & \frac{1}{r} \frac{\partial}{\partial r} \left[r D \frac{\partial C(\vec{r}, t)}{\partial r} \right] + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left[D \frac{\partial C(\vec{r}, t)}{\partial \phi} \right] + \frac{\partial}{\partial z} \left[D \frac{\partial C(\vec{r}, t)}{\partial z} \right] - \\ & - \frac{1}{r} \frac{\partial}{\partial r} [r C(\vec{r}, t) v_r(\vec{r}, t)] - \frac{1}{r} \frac{\partial}{\partial \phi} [C(\vec{r}, t) v_\phi(\vec{r}, t)] - \frac{\partial}{\partial z} [C(\vec{r}, t) v_z(\vec{r}, t)]. \end{aligned} \quad (11)$$

Farther we transform the above differential equations to the following integro- differential form

$$\begin{aligned} T(\vec{r}, \tau) = & T(\vec{r}, \tau) + \frac{1}{4\pi R^2 L} \left[\Gamma_r + \Gamma_\phi + \Gamma_z - \Lambda_r - \Lambda_\phi - \Lambda_z + \int_0^t \int_R^r u^2 p(\vec{r}, \tau) du d\tau + \right. \\ & \left. + \sigma R^2 \int_0^t T^4(R, \phi, z, t) d\tau - \int_R^r u^2 T(\vec{r}, \tau) du + (r^3 - R^3) \frac{T_r}{3} \right], \end{aligned} \quad (10a)$$

$$\begin{aligned} C(\vec{r}, \tau) = & C(\vec{r}, \tau) + \frac{1}{4\pi R^2 L} \left[r \int_0^t D \frac{\partial C(\vec{r}, \tau)}{\partial r} d\tau + \frac{\partial \tilde{\Gamma}_{\phi 0}(\vec{r}, \tau)}{\partial \phi} - \int_R^r u^2 C(\vec{r}, \tau) du + \right. \\ & + \frac{\partial \tilde{\Gamma}_{z 2}(\vec{r}, \tau)}{\partial z} - \tilde{\Gamma}_{r 1}(\vec{r}, \tau) - r^2 \int_0^t C(\vec{r}, \tau) v_r(\vec{r}, \tau) d\tau - \frac{\partial \tilde{\Lambda}_{\phi 1}(\vec{r}, \tau)}{\partial \phi} - \frac{\partial \tilde{\Lambda}_{z 1}(\vec{r}, \tau)}{\partial z} + \\ & \left. + \tilde{\Lambda}_{r 1}(\vec{r}, \tau) + C_0(t) \delta(z + L) \right], \end{aligned} \quad (11a)$$

where

$$\begin{aligned} \Gamma_\rho(\vec{r}, \tau) = & \lambda \int_0^t \int_R^r u \frac{\partial^2 T(\vec{r}, \tau)}{\partial \rho^2} du d\tau, \quad \Lambda_\rho(\vec{r}, \tau) = c \frac{\partial}{\partial \rho} \int_0^t \int_R^r u^2 v_\rho(\vec{r}, \tau) C(\vec{r}, \tau) T(\vec{r}, \tau) du d\tau, \\ \tilde{\Gamma}_{\rho i}(\vec{r}, \tau) = & \int_0^t \int_R^r u^i D \frac{\partial C(\vec{r}, \tau)}{\partial \rho} du d\tau, \quad \tilde{\Lambda}_{\rho i}(\vec{r}, \tau) = \int_0^t \int_R^r u^i C(\vec{r}, \tau) v_\rho(\vec{r}, \tau) du d\tau. \end{aligned}$$

To determine spatio-temporal distributions of temperature and concentration of mixture of gases we used method of averaging of function corrections. To determine the first-order approximations of the required functions we replace the functions in right sides of Eqs. (10a) and (11a) on their average values α_{1T} and α_{1C} . In this situation the first-order approximations could be written in this form

$$\begin{aligned}
T_1(\vec{r}, \tau) &= \alpha_{1T} + \frac{1}{4\pi R^2 L} \left[2c\alpha_{1T}\alpha_{1C}V_r(\vec{r}, \tau) - c\alpha_{1T}\alpha_{1C} \int_0^t r^2 v_r(\vec{r}, \tau) d\tau - c\alpha_{1T} \frac{\partial V_\phi(\vec{r}, \tau)}{\partial \phi} \times \right. \\
&\times \alpha_{1C} - c\alpha_{1T}\alpha_{1C} \frac{\partial V_z(\vec{r}, \tau)}{\partial z} + \int_0^t \int_R^r u^2 p(\vec{r}, \tau) du d\tau + \frac{T_r}{3}(r^3 - R^3) - \frac{\alpha_{1T}}{3}(r^3 - R^3) + \sigma R^2 \alpha_{1T}^4 \left. \right], \\
C_1(r, \phi, z, t) &= \alpha_{1C} + \frac{1}{4\pi R^2 L} \left[\alpha_{1C} \int_0^t \int_R^r u v_r(u, \phi, z, \tau) du d\tau - \frac{\partial}{\partial \phi} \int_0^t \int_R^r u v_\phi(u, \phi, z, \tau) du d\tau \times \right. \\
&\times \alpha_{1C} - \alpha_{1C} \frac{\partial}{\partial z} \int_0^t \int_R^r u^2 v_z(u, \phi, z, \tau) du d\tau - \frac{\alpha_{1C}}{3}(r^3 - R^3) - r^2 \alpha_{1C} \int_0^t v_r(r, \phi, z, \tau) d\tau + C_0(t) \times \\
&\times \delta(z + L) \left. \right].
\end{aligned}$$

where $V_r(\vec{r}, \tau) = \int_0^t \int_R^r u v_r(\vec{r}, \tau) du d\tau$.

We determine the average values α_{1T} and α_{1C} by standard relations, which are analogous to relations (6)

$$\alpha_{1T} = \int_0^{\Theta R} \int_0^{2\pi} \int_{-L}^L \int T_1 dz d\phi dr dt, \quad \alpha_{1C} = \int_0^{\Theta R} \int_0^{2\pi} \int_{-L}^L \int C_1 dz d\phi dr dt. \quad (12)$$

Substitution of the first- and the second-order approximations of concentrations and temperature into relation (12) gives us possibility to obtain the following result

$$\alpha_{1T} = \sqrt{\frac{y}{2}} + \frac{1}{2} \sqrt{2y + \frac{4}{\sqrt{8y}}(y - E)} \quad , \quad \alpha_{1C} G + \pi R^2 \int_0^\Theta C_0(t) dt = 0$$

where $E = \frac{4}{5} \pi L \Theta R^5 - 2c \int_0^\Theta (\Theta - t) \int_0^R r^3 \int_{-L}^{2\pi} \int v_r(\vec{r}, t) dz d\phi dr dt - c \pi V_0 \Theta R^2$, $F = \frac{2}{5} \pi L \times$
 $\times T_r R^5 \Theta^2 + \frac{1}{2} \int_0^{\Theta R} \int_0^{2\pi} \int_{-L}^L \int p(\vec{r}, t) dz d\phi dr dt$, $y = \sqrt[3]{\frac{F^2}{256} + \frac{E^3}{13824} - \frac{F}{16}} - \sqrt[3]{\frac{F^2}{256} + \frac{E^3}{13824} + \frac{F}{16}}$,
 $G = \frac{1}{2} \int_0^\Theta (\Theta - t) \int_0^R r^3 \int_{-L}^{2\pi} \int v_{1z}(\vec{r}, t) dz d\phi dr dt - \frac{1}{2} \int_0^\Theta (\Theta - t) \int_0^R r^3 \int_{-L}^{2\pi} \int v_r(\vec{r}, t) dz d\phi dr dt +$
 $+ 3\pi L R^5 \frac{\Theta}{5}$.

The second-order approximations of temperature and concentration of mixture of gases we determine framework standard procedure of method of averaging of function corrections [12-15], i.e. by replacement of the required functions in the right sides of Eqs. (10a) and (11a) on the following sums $T \rightarrow \alpha_{2T} + T_1$, $C \rightarrow \alpha_{2C} + T_{1T}$. In this situation the second-order approximations of required functions could be written as

$$\begin{aligned}
T_2(\vec{r}, t) &= \alpha_{2T} + T_1(\vec{r}, \tau) + \frac{1}{4\pi R^2 L} \left\{ \lambda r^2 \int_0^t \frac{\partial T_1(\vec{r}, \tau)}{\partial r} d\tau - 2\lambda W_{r11}(\vec{r}, t) + \lambda W_{\phi 01}(\vec{r}, t) + \right. \\
&+ \lambda W_{z21}(\vec{r}, t) - c \cdot r^2 \int_0^t [\alpha_{2C} + C_1(\vec{r}, \tau)] [\alpha_{2T} + T_1(\vec{r}, \tau)] v_r(\vec{r}, \tau) d\tau + 2c \Phi_{r01}(\vec{r}, t) -
\end{aligned}$$

$$\begin{aligned}
& -c \Phi_{\phi 11}(\vec{r}, t) - c \Phi_{z 12} + \int_0^t \int_R^r u^2 p(\vec{r}, \tau) du d\tau + \sigma R^2 \int_0^t [\alpha_{2T} + T_1(\vec{r}, \tau)]^4 d\tau + (r^3 - R^3) \frac{T_r}{3} - \\
& \quad - \int_R^r u^2 [\alpha_{2T} + T_1(\vec{r}, \tau)] du \Big\} , \\
C_2(\vec{r}, t) = & C_1(\vec{r}, t) + \frac{1}{4\pi R^2 L} \left\{ \frac{\partial \tilde{W}_{\phi 01}(\vec{r}, t)}{\partial \phi} - \tilde{W}_{r 11}(\vec{r}, t) + \frac{\partial \tilde{W}_{z 11}(\vec{r}, t)}{\partial z} + \tilde{\Phi}_{r 01}(\vec{r}, t) - \right. \\
& - \tilde{\Phi}_{\phi 11}(\vec{r}, t) - \tilde{\Phi}_{z 12}(\vec{r}, t) + r^2 \int_0^t D \frac{\partial C_1(\vec{r}, \tau)}{\partial r} d\tau - r^2 \int_0^t [\alpha_{2C} + C_1(\vec{r}, \tau)] v_r(\vec{r}, \tau) d\tau + \\
& \left. + C_0(t) \delta(z + L) - \int_R^r u^2 [\alpha_{2C} + C_1(\vec{r}, \tau)] du \right\} + \alpha_{2C} ,
\end{aligned}$$

where $W_{\rho ij}(\vec{r}, t) = \int_0^t \int_R^r u^i \frac{\partial T_j(\vec{r}, \tau)}{\partial \rho} du d\tau$, $\Phi_{\rho ij}(\vec{r}, t) = \frac{\partial^i}{\partial \rho^i} \int_0^t \int_R^r u^j v_\rho(\vec{r}, \tau) [\alpha_{2T} + T_1(\vec{r}, \tau)] \times$
 $\times [\alpha_{2C} + C_1(\vec{r}, \tau)] du d\tau$, $\tilde{\Phi}_{\rho ij}(\vec{r}, t) = \frac{\partial^i}{\partial \rho^i} \int_0^t \int_R^r u [\alpha_{2C} + C_1(\vec{r}, \tau)] v_\rho(\vec{r}, \tau) du d\tau$, $\tilde{W}_{\rho ij}(\vec{r}, t) =$
 $= \int_0^t \int_R^r u^i D \frac{\partial C_1(\vec{r}, \tau)}{\partial \rho} du d\tau$.

We determine average values of the second-order approximations of temperature and concentration of mixture α_{2T} and α_{2C} by using the following standard relation

$$\alpha_{2T} = \int_0^R \int_0^{2\pi} \int_{-L}^L (T_2 - T_1) dz d\phi dr dt, \quad \alpha_{2C} = \int_0^R \int_0^{2\pi} \int_{-L}^L (C_2 - C_1) dz d\phi dr dt. \quad (13)$$

Substitution of the first- and the second- order approximations of temperature and concentration into relations (13) gives us possibility to obtain equations for required average values in the following form

$$\begin{aligned}
& -\frac{\lambda}{2} G_{r 311} + \lambda G_{\phi 212} + \lambda G_{z 412} - c \int_0^\Theta (\Theta - t) \int_0^R \int_0^{2\pi} \int_{-L}^L [\alpha_{2C} + C_1(r, \phi, z, t)] [\alpha_{2T} + T_1(r, \phi, z, t)] \times \\
& \times v_r(r, \phi, z, t) dz d\phi r^2 dr dt + \sigma V_0 \frac{c}{2} \int_0^\Theta (\Theta - t) \int_0^R r^4 \int_0^{2\pi} \int_{-L}^L [\alpha_{2T} + T_1(r, \phi, z, t)]^4 dz d\phi dr \times \\
& \times C_0(t) dt + 2\pi L \Theta R^5 \frac{T_r}{5} + \frac{1}{2} \int_0^\Theta (\Theta - t) \int_0^R r^4 \int_0^{2\pi} \int_{-L}^L p(r, \phi, z, t) dz d\phi dr dt + R^2 \int_0^\Theta (\Theta - t) \times \\
& \times \sigma \int_0^R \int_0^{2\pi} \int_{-L}^L [\alpha_{2T} + T_1(r, \phi, z, t)]^4 dz d\phi dr dt + \frac{1}{2} \int_0^\Theta \int_0^R \int_0^{2\pi} \int_{-L}^L [\alpha_{2T} + T_1(r, \phi, z, t)] dz d\phi \times \\
& \times r^4 dr dt = 0 , \\
& -\frac{1}{2} \int_0^\Theta (\Theta - t) \int_0^R r^3 \int_0^{2\pi} \int_{-L}^L [\alpha_{2C} + C_1(r, \phi, z, t)] v_r(r, \phi, z, t) dz d\phi dr dt + \frac{1}{2} \int_0^\Theta (\Theta - t) \int_0^R r^3 \int_0^{2\pi} \int_{-L}^L D \times
\end{aligned}$$

$$\begin{aligned}
& \times \frac{\partial C_1(r, \phi, z, t)}{\partial r} dz d\phi dr dt + \frac{1}{2} \int_0^\Theta \int_0^R r^4 \int_0^{2\pi} \int_{-L}^L [\alpha_{2C} + C_1(r, \phi, z, t)] dz d\phi dr dt + \int_0^\Theta (\Theta - t) \times \\
& \times \frac{V_0}{2} \int_0^R r^4 \int_0^{2\pi} \int_{-L}^L [\alpha_{2C} + C_0(t)] dz d\phi dr dt + \pi R^5 L \int_0^\Theta C_0(t) dt - \int_0^\Theta (\Theta - t) \int_0^R \int_0^{2\pi} \int_{-L}^L v_r(r, \phi, z, \tau) \times \\
& \times [\alpha_{2C} + C_1(r, \phi, z, \tau)] dz d\phi r^3 dr dt = 0.
\end{aligned}$$

$$\text{where } G_{\rho^{ijk}} = \int_0^\Theta (\Theta - t) \int_0^R r^i \int_0^{2\pi} \int_{-L}^L \frac{\partial^k T_j(r, \phi, z, t)}{\partial \rho^k} dz d\phi dr dt.$$

The obtained system of equations for the average values α_{2T} and α_{2C} could be solved by standard approaches [16]. However the obtained solution is bulky due to nonlinear dependence of diffusion coefficient on temperature. In this situation we will not present the solution in this work.

3. Discussion

In this section based on calculated in previous section relations for spatio-temporal distributions of temperature, components of velocity of flow of mixture of gases and their concentration we analyzed dynamics of temperature in keeper of substrate and in heterostructure grown. During initial stage one can find heating of keeper of substrate and of heterostructure grown. Time of heating could be estimated by approach, described in [16]. Value of this time is approximately equal to $9 \approx (6\pi - 1)R^2/24D_0$. Farther one can find stationary regime. After that heating of the considered system will be continued due to heating of scin-layer of keeper of substrate and of heterostructure grown. At the same time one can losing of heat due to convective heat transfer and thermal radiation. To obtain heterostructure with as much as possible homogeneity of it's properties it is practicably to make distribution of temperature with as much as possible homogeneity in stationary regime of growth. At the same time one can obtain increasing of homogeneity of distribution of temperature in keeper of substrate. To increase the homogeneity the obtaining by heterostructure heat should compensate losing of heat due to convective heat transfer and thermal radiation. In this situation it should be performed the following

$$\text{condition: } \int_0^R r \cdot p(r, \phi, z, t) dr \approx \sigma \cdot T^4(R, \phi, z, t) + \Theta \cdot v_z(R, \phi, z, t) / 4\pi LR^2.$$

4. Conclusion

In this paper we introduce an approach to increase homogeneity of distribution of temperatures in their depth during grown from gas phase. Increasing of homogeneity of temperature in depth of heterostructure gives us possibility to increase homogeneity of properties of appropriate materials of heterostructure grown. At the same time we introduce an analytical approach to model technological process: distribution of temperature, mixture of gases (materials for growth of heterostructure in gas phase and gas-carrier) and components of velocity of mixture of gases in vertical reactor from gas phase.

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Appendix

Integral form of equations for components of velocity of flow of composition of gases (gas-carrier and materials in gas phase, which are used for formation epitaxial layer) v_r , v_ϕ and v_z could be written as

$$v_r = v_r + \frac{V}{2RL} \{ S_{rr010100}(\vec{r}, t) + S_{rr000100}(\vec{r}, t) + S_{rz000100}(\vec{r}, t) - S_{zr0000001}(\vec{r}, t) -$$

$$\begin{aligned}
& -S_{tr1011100}(\vec{r},t) - S_{tr0011210}(\vec{r},t) - \frac{1}{2}S_{tr0012100}(\vec{r},t) - \frac{1}{2}S_{rr1012210}(\vec{r},t) - \frac{1}{2}S_{rz1002100}(\vec{r},t) - \\
& -S_{\varphi\varphi1012210}(\vec{r},t) + rS_{rr0011100}(\vec{r},t)\Big|_{r=R} - S_{rr0001000}(\vec{r},t)\Big|_{r=R} + rS_{tr0011210}(\vec{r},t)\Big|_{r=R} + r \times \\
& \times S_{zr0001000}(\vec{r},t) + \frac{r}{2}S_{rr0012210}(\vec{r},t)\Big|_{r=R} - S_{rr1001000}(\vec{r},t)\Big|_{r=R} - S_{rz0001000}(\vec{r},t) + \frac{r}{2}S_{zz0012210}(\vec{r},t) - \\
& -S_{rr1011100}(\vec{r},t) + \frac{r}{2}S_{\varphi\varphi1002210}(\vec{r},t) - S_{tr1011210}(\vec{r},t) - \frac{1}{2}S_{rr1012100}(\vec{r},t) - \frac{1}{2}S_{r\varphi0012210}(\vec{r},t) - \\
& -\frac{1}{2}S_{rz0002100}(\vec{r},t) - \frac{1}{2}S_{zz0002210}(\vec{r},t) + \frac{1}{2}S_{rr0012100}(\vec{r},t)\Big|_{r=R} - R S_{rr0001000}(\vec{r},t) - [S_{rr1011100}(\vec{r},t)\Big|_{z=-L} - \\
& -S_{tr0011210}(\vec{r},t)\Big|_{z=-L} - \frac{1}{2}S_{rr1012210}(\vec{r},t)\Big|_{z=-L} - S_{rr0001000}(\vec{r},t)\Big|_{z=-L} - \frac{1}{2}S_{rr0012100}(\vec{r},t)\Big|_{z=-L} - \\
& + \frac{1}{2}S_{\varphi\varphi1012210}(\vec{r},t)\Big|_{z=-L} + S_{zz0001000}(\vec{r},t)\Big|_{z=-L} + \frac{1}{2}S_{\varphi\varphi0012210}(\vec{r},t)\Big|_{z=-L} - rS_{tr0011210}(\vec{r},t)\Big|_{r=R} + \\
& -\frac{1}{2}S_{\varphi\varphi0012210}(\vec{r},t)\Big|_{r=R} + rS_{tr0011210}(\vec{r},t)\Big|_{r=R} + rS_{rr0011100}(\vec{r},t)\Big|_{r=R} + S_{rr0010001}(\vec{r},t)\Big|_{r=R} + \frac{r}{2} \times \\
& \times S_{rr0012210}(\vec{r},t)\Big|_{r=R} + S_{rr0001000}(\vec{r},t)\Big|_{r=R} - \frac{V_0^2}{2}S_{rr0000100}(\vec{r},t)\Big|_{r=R} + \frac{1}{2}S_{rr0012100}(\vec{r},t)\Big|_{r=R} + \\
& + S_{rr0012100}(\vec{r},t)\Big|_{r=R} + \frac{r}{2}S_{\varphi\varphi0002210}(\vec{r},t)\Big|_{r=R} + \frac{r}{2}S_{zz0012210}(\vec{r},t)\Big|_{r=R} - S_{t\varphi1010011}(\vec{r},t)\Big|_{r=R} + \\
& + \frac{1}{2}S_{rr0012100}(\vec{r},t)\Big|_{r=R} - S_{tr1011210}(\vec{r},t)\Big|_{r=R} + S_{zz0001000}(\vec{r},t)\Big|_{r=R} + \frac{1}{2}S_{zz0002100}(\vec{r},t)\Big|_{r=R} - \\
& -\frac{1}{2}S_{\varphi\varphi0012210}(\vec{r},t)\Big|_{r=R} + \frac{1}{2}S_{zz0002210}(\vec{r},t)\Big|_{r=R} - \frac{1}{2}S_{rr1012210}(\vec{r},t)\Big|_{r=R} + \int_0^t \int_0^\varphi \int_0^0 \frac{P}{\rho} dw dv d\tau \Big] \frac{z}{L} - \\
& - \int_0^t \int_0^r \int_0^\varphi \int_0^z \frac{P}{\rho} dw dv d\tau + \int_0^t \int_0^r \int_0^\varphi \int_0^z \frac{P}{\rho} dw dv du d\tau \Big\},
\end{aligned}$$

$$\begin{aligned}
v_\varphi &= v_\varphi + \frac{v}{2LR} (S_{rr0011000}(\vec{r},t) - rS_{rr0010001}(\vec{r},t) - S_{z\varphi2100001}(\vec{r},t) + S_{rr1001000}(\vec{r},t) + S_{r\varphi2111100}(\vec{r},t) + \\
& + \frac{r^2}{2}S_{rr0111101}(\vec{r},t) + S_{t\varphi2111210}(\vec{r},t) - S_{rr2112100}(\vec{r},t) - S_{rr2112100}(\vec{r},t) + \frac{1}{2}S_{rr2112210}(\vec{r},t) + \\
& + \frac{1}{2}S_{zz2102100}(\vec{r},t) + \frac{1}{2}S_{\varphi\varphi1012100}(\vec{r},t) + \frac{1}{2}S_{zz2112210lmno}(\vec{r},t) + \frac{\varphi}{2\pi} \left[rS_{rr0010001}(\vec{r},t)\Big|_{z=2\pi} - \right.
\end{aligned}$$

$$\begin{aligned}
& -\frac{r^2}{2}S_{rr0111101}(\vec{r},t)\Big|_{z=2\pi} - S_{rr0010001}(\vec{r},t)\Big|_{z=2\pi} - S_{rr0001000}(\vec{r},t)\Big|_{z=2\pi} - S_{t\varphi2110011}(\vec{r},t)\Big|_{z=2\pi} - \\
& - S_{t\varphi2111210}(\vec{r},t)\Big|_{z=2\pi} + S_{z\varphi1100001}(\vec{r},t)\Big|_{z=2\pi} + S_{rr2112100}(\vec{r},t)\Big|_{z=2\pi} - \frac{1}{2}S_{rr2112210}(\vec{r},t)\Big|_{z=2\pi} - \\
& - \frac{1}{2}S_{zz2102100}(\vec{r},t)\Big|_{z=2\pi} - \frac{1}{2}S_{zz2112210}(\vec{r},t)\Big|_{z=2\pi} - \frac{1}{2}S_{\varphi\varphi1012100}(\vec{r},t)\Big|_{z=2\pi} \Big] - (2\pi - \varphi)\omega^2 r^4 t \frac{\varphi}{4} + \\
& + \frac{z}{L} \left\{ r^2 S_{rr0010001}(\vec{r},t)\Big|_{z=L} - r S_{rr0011000}(\vec{r},t)\Big|_{z=L} - S_{rr0011000}(\vec{r},t)\Big|_{z=L} - \frac{r^2}{2} S_{zr0111101}(\vec{r},t)\Big|_{z=L} - \right. \\
& - S_{t\varphi2110101}(\vec{r},t)\Big|_{z=L} - S_{t\varphi2111210}(\vec{r},t)\Big|_{z=L} - \frac{1}{2} S_{rr2112210}(\vec{r},t)\Big|_{z=L} - S_{rr2112100}(\vec{r},t)\Big|_{z=L} - \\
& - S_{rr0001000}(\vec{r},t)\Big|_{z=L} - \frac{1}{2} S_{zz2112210}(\vec{r},t)\Big|_{z=L} - \frac{1}{2} S_{\varphi\varphi1012100}(\vec{r},t)\Big|_{z=L} - \frac{1}{2} S_{zz2102100}(\vec{r},t) - \\
& - \left[r S_{rr0010001}(\vec{r},t)\Big|_{\varphi=2\pi} - S_{rr0011000}(\vec{r},t)\Big|_{\varphi=2\pi} - r^2 S_{rr0111101}(\vec{r},t)\Big|_{\varphi=2\pi} - S_{rr0001000}(\vec{r},t)\Big|_{\varphi=2\pi} - \right. \\
& - S_{t\varphi2111210}(\vec{r},t)\Big|_{z=L} - S_{t\varphi2110101}(\vec{r},t)\Big|_{z=L} - \frac{1}{2} S_{rr2112210}(\vec{r},t)\Big|_{\varphi=2\pi}^{z=L} + S_{rr2112100}(\vec{r},t)\Big|_{\varphi=2\pi}^{z=L} - \\
& - \frac{1}{2} S_{rz2102100}(\vec{r},t)\Big|_{\varphi=2\pi}^{z=L} - \frac{1}{2} S_{zz2102210}(\vec{r},t)\Big|_{\varphi=2\pi}^{z=L} \Big] \frac{\varphi}{2\pi} + (2\pi - \varphi)\omega^2 r^4 t \frac{\varphi}{4} \Big\} - \int_0^t \int_0^r \int_0^z \frac{P}{\rho} dw du d\tau \Big), \\
v_z = & \frac{\nu}{2RL} \left\{ S_{zr1100001}(\vec{r},t) + S_{rz0110001}(\vec{r},t) + S_{zz1011000}(\vec{r},t) - \frac{1}{2} S_{rr1112210}(\vec{r},t) - \frac{1}{2} S_{rr1112100}(\vec{r},t) - \right. \\
& - S_{tz1111210}(\vec{r},t) - \frac{1}{2} S_{\varphi\varphi0112210}(\vec{r},t) - \frac{1}{2} S_{zz1112210}(\vec{r},t) - S_{zz1111100}(\vec{r},t) - \frac{1}{2} S_{zz1112100}(\vec{r},t) - \\
& - \frac{1}{2} S_{\varphi\varphi0112100}(\vec{r},t) - \frac{z}{L} \left[r S_{rz0110001}(\vec{r},t)\Big|_{z=-L} - S_{t\varphi1110101}(\vec{r},t)\Big|_{z=-L} - S_{tz1110211}(\vec{r},t)\Big|_{z=-L} + r^2 \times \right. \\
& \times S_{rr0111101}(\vec{r},t)\Big|_{z=-L} + \frac{1}{2} S_{rr1112210}(\vec{r},t)\Big|_{z=-L} + S_{\varphi\varphi1010001}(\vec{r},t)\Big|_{z=-L} - \frac{1}{2} S_{\varphi\varphi1012100}(\vec{r},t)\Big|_{z=-L} - \\
& - \frac{1}{2} S_{zz1102100}(\vec{r},t)\Big|_{z=-L} - \frac{1}{2} S_{zz1112210}(\vec{r},t)\Big|_{z=-L} - \frac{L}{2} S_{zz1102210}(\vec{r},t)\Big|_{z=-L} - \frac{1}{2} S_{\varphi\varphi1012210}(\vec{r},t)\Big|_{z=-L} \Big] - \\
& \left. - \int_0^t \int_0^r (r-u) \int_0^\varphi (\varphi-v) \frac{P}{\rho} dv du d\tau \right\} + v_z,
\end{aligned}$$

where $S_{\rho\gamma ijklmno}(\vec{r},t) = \int_0^t \int_0^r (r-u)^i \int_0^\varphi (\varphi-v)^j \int_0^z (z-w)^k \frac{v_\gamma^l}{v^m} \left(\frac{\partial v}{\partial \rho} \right)^n \left(\frac{\partial v_\gamma}{\partial \rho} \right)^o dw dv du d\tau$.

The first-order approximations of components of velocity of flow of composition of gases (gas-carrier and materials in gas phase, which are used for formation epitaxial layer) v_r , v_φ and v_z could be written as

$$\begin{aligned}
 v_{1r} = & \alpha_{1r} + \frac{v}{2LR} \left\{ \alpha_{1r} \varphi^2 R z \frac{t}{2} + \alpha_{1r} t r \varphi z + \alpha_{1z} t r \varphi z - \alpha_{1r} S_{tr1010210}(\vec{r}, t) - \alpha_{1r} r^2 \varphi \frac{t}{2} - \alpha_{1r} \times \right. \\
 & \times S_{tr1010100}(\vec{r}, t) - \frac{\alpha_{1r}^2}{2} S_{rr0010100}(\vec{r}, t) - \frac{\alpha_{1z}^2}{2} S_{rr1000100}(\vec{r}, t) - \frac{\alpha_{1r}^2}{2} S_{rr1010210}(\vec{r}, t) - S_{\varphi\varphi1010210}(\vec{r}, t) \times \\
 & \times \frac{\alpha_{1\varphi}^2}{2} - \frac{\alpha_{1z}^2}{2} S_{zz1010210}(\vec{r}, t) - \alpha_{1r} r S_{tr0010210}(\vec{r}, t) + \alpha_{1r} r S_{tr0010210}(\vec{r}, t) + \alpha_{1r}^2 \frac{r}{2} S_{rr0010210}(\vec{r}, t) + \\
 & + \alpha_{1r} R \varphi (r - z) t + \alpha_{1z}^2 \frac{r}{2} S_{zz0110210}(\vec{r}, t) \Big|_{r=R} - \alpha_{1r} S_{tr1010210}(\vec{r}, t) - \alpha_{1r} R (2R + z) \varphi t + \alpha_{1r} \times \\
 & \times S_{tz1010210}(\vec{r}, t) \Big|_{r=R} + \alpha_{1\varphi}^2 \frac{r}{2} S_{\varphi\varphi0000210}(\vec{r}, t) \Big|_{r=R} - \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi0010210}(\vec{r}, t) \Big|_{r=R} - S_{rr0000100}(\vec{r}, t) \Big|_{r=R} \times \\
 & \times \frac{\alpha_{1z}^2}{2} - \frac{\alpha_{1r}^2}{2} S_{rr1010210}(\vec{r}, t) \Big|_{r=R} + \frac{\alpha_{1r}^2}{2} S_{rr0010100}(\vec{r}, t) \Big|_{r=R} - \frac{\alpha_{1z}^2}{2} S_{zz0000210}(\vec{r}, t) \Big|_{r=R} - \alpha_{1r} t R^2 \varphi - \\
 & - \frac{z}{L} \left[\alpha_{1r} t r \varphi L - \alpha_{1r} S_{rr1010100}(\vec{r}, t) \Big|_{z=-L} - \alpha_{1r} S_{tr1010210}(\vec{r}, t) \Big|_{z=-L} - \frac{\alpha_{1r}^2}{2} S_{rr1010210}(\vec{r}, t) \Big|_{z=-L} - \right. \\
 & - \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi0010210}(\vec{r}, t) \Big|_{z=-L} + \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi1010210}(\vec{r}, t) \Big|_{z=-L} - \frac{\alpha_{1r}^2}{2} S_{rr0010100}(\vec{r}, t) \Big|_{z=-L} - S_{rr0000100}(\vec{r}, t) \Big|_{r=R} \times \\
 & \times \frac{V_0^2}{2} + \alpha_{1z} t r \varphi L - \alpha_{1r} r S_{tr0010210}(\vec{r}, t) \Big|_{z=-L} + \alpha_{1r}^2 \frac{r}{2} S_{rr0010210}(\vec{r}, t) \Big|_{z=-L} + S_{tr0010210}(\vec{r}, t) \Big|_{z=-L} \times \\
 & \times \alpha_{1r} r + \alpha_{1\varphi}^2 \frac{r}{2} S_{\varphi\varphi0000210}(\vec{r}, t) \Big|_{z=-L} + \alpha_{1r} \varphi L^2 \frac{t}{2} + \alpha_{1r} S_{tr1010210}(\vec{r}, t) \Big|_{z=-L} + \alpha_{1r} \varphi t L \left(R + \frac{L}{2} \right) + \\
 & + \alpha_{1z}^2 \frac{r}{2} S_{zz0110210}(\vec{r}, t) \Big|_{z=-L} - \alpha_{1r} S_{tr1010210}(\vec{r}, t) \Big|_{z=-L} + \frac{\alpha_{1r}^2}{2} S_{rr0010100}(\vec{r}, t) \Big|_{z=-L} + S_{rr0010100}(\vec{r}, t) \Big|_{z=-L} \times \\
 & \times \frac{\alpha_{1r}^2}{2} - \alpha_{1z} t \varphi R L - \frac{\alpha_{1r}^2}{2} S_{rr1010210}(\vec{r}, t) \Big|_{z=-L} + \frac{\alpha_{1z}^2}{2} S_{zz0000210}(\vec{r}, t) \Big|_{z=-L} + \int_0^t \int_0^\varphi \int_{-L}^0 \frac{P}{\rho} dw dv d\tau + \\
 & + \frac{\alpha_{1z}^2}{2} S_{rr0000100}(\vec{r}, t) \Big|_{z=-L} + \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi0010210}(\vec{r}, t) \Big|_{z=-L} \left. - \int_0^t \int_0^\varphi \int_0^z \int_0^0 \frac{P}{\rho} dw dv du d\tau \right\}, \\
 v_{1\varphi} = & \alpha_{1\varphi} + \frac{v}{2LR} \left(\alpha_{1r} t r \varphi z - \alpha_{1\varphi} t r^2 \varphi^2 + \alpha_{1\varphi} S_{rr2110100}(\vec{r}, t) - \alpha_{1r}^2 \frac{r^2}{2} S_{rr0110210}(\vec{r}, t) + \right. \\
 & + \alpha_{1\varphi} S_{tr2110210}(\vec{r}, t) - \alpha_{1r}^2 S_{rr2110100}(\vec{r}, t) + \frac{\alpha_{1r}^2}{2} S_{rr2110210}(\vec{r}, t) + \frac{\alpha_{1z}^2}{2} S_{rr2110100}(\vec{r}, t) + \frac{\alpha_{1\varphi}^2}{2} \times
 \end{aligned}$$

$$\begin{aligned}
& \times S_{rr1010100}(\vec{r}, t) + \frac{\alpha_{1z}^2}{2} S_{zz2110210}(\vec{r}, t) + \left[\alpha_{1r}^2 \frac{r^2}{2} S_{rr0110200}(\vec{r}, t) \Big|_{\varphi=2\pi} + \alpha_{1\varphi} S_{tr2110210}(\vec{r}, t) \Big|_{\varphi=2\pi} - \right. \\
& - \alpha_{1\varphi} S_{tr2110210}(\vec{r}, t) \Big|_{\varphi=2\pi} + \frac{\alpha_{1r}^2}{2} S_{rr2110100}(\vec{r}, t) \Big|_{\varphi=2\pi} - \pi \alpha_{1r} t z^2 - \frac{\alpha_{1z}^2}{2} S_{zz2110210}(\vec{r}, t) \Big|_{\varphi=2\pi} + \\
& + 2\alpha_{1\varphi} \pi^2 t r^2 - \frac{\alpha_{1\varphi}^2}{2} S_{rr1010100}(\vec{r}, t) \Big|_{\varphi=2\pi} - \frac{\alpha_{1z}^2}{2} S_{rr2100100}(\vec{r}, t) \Big|_{\varphi=2\pi} \left. \right] \frac{\varphi}{2\pi} - (2\pi - \varphi) \omega^2 r^4 t \frac{\varphi}{4} + \\
& + \frac{z}{L} \left\{ \alpha_{1\varphi} S_{t\varphi2110200}(\vec{r}, t) \Big|_{z=L} + \alpha_{1\varphi} S_{tr2110200}(\vec{r}, t) \Big|_{z=L} - \alpha_{1\varphi} S_{tr2110210}(\vec{r}, t) \Big|_{z=L} + S_{rr0110210}(\vec{r}, t) \times \right. \\
& \times \alpha_{1r}^2 \frac{r^2}{2} - \frac{\alpha_{1r}^2}{2} S_{rr2110210}(\vec{r}, t) \Big|_{z=L} - \alpha_{1r}^2 S_{rr2110100}(\vec{r}, t) \Big|_{z=L} - \frac{\alpha_{1z}^2}{2} S_{rr2100100}(\vec{r}, t) \Big|_{z=L} - \alpha_{1r} r t \varphi \times \\
& \times L - \frac{\alpha_{1z}^2}{2} S_{zz2110211}(\vec{r}, t) \Big|_{z=L} - \frac{\alpha_{1\varphi}^2}{2} S_{rr1010100}(\vec{r}, t) \Big|_{z=L} - \frac{\varphi}{2\pi} \left[\alpha_{1r}^2 S_{rr2110100}(\vec{r}, t) \Big|_{z=L} - 2\pi \alpha_{1r} \times \right. \\
& \times t r L - \alpha_{1\varphi} S_{tr2110210}(\vec{r}, t) \Big|_{z=L} + \alpha_{1r}^2 \frac{r^2}{2} S_{rr0110100}(\vec{r}, t) \Big|_{z=L} + \alpha_{1\varphi} S_{tr2110100}(\vec{r}, t) \Big|_{z=L} - \frac{\alpha_{1r}^2}{2} \times \\
& \times S_{rr2110210}(\vec{r}, t) \Big|_{z=L} - \frac{\alpha_{1z}^2}{2} S_{zz2100210}(\vec{r}, t) \Big|_{z=L} - \frac{\alpha_{1\varphi}^2}{2} S_{rr1010100}(\vec{r}, t) \Big|_{z=L} - S_{rr2102100100}(\vec{r}, t) \Big|_{z=L} \times \\
& \times \frac{\alpha_{1z}^2}{2} \left. \right] + (2\pi - \varphi) \omega^2 r^4 t \frac{\varphi}{4} \Big\} - \int_0^t \int_0^r \int_0^z u \int_0^P \frac{P}{\rho} dw du d\tau \Bigg) , \\
& v_{1z} = \alpha_{1z} + \frac{v}{2RL} \left\{ \alpha_{1z} t \varphi \frac{z^2}{2} \left(\frac{\varphi}{2} + 1 \right) - \frac{\alpha_{1r}^2}{2} S_{rr1110210}(\vec{r}, t) + \alpha_{1r} t r^2 \frac{\varphi^2}{4} - S_{111110100}(\vec{r}, t) \times \right. \\
& \times \frac{\alpha_{1r}^2}{2} - \alpha_{1z} S_{tr1110210}(\vec{r}, t) - \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi0110210}(\vec{r}, t) + \frac{\alpha_{1z}^2}{2} S_{zz1110210}(\vec{r}, t) - \alpha_{1z} S_{rr1110100}(\vec{r}, t) - \\
& - \frac{\alpha_{1z}^2}{2} S_{rr1110100}(\vec{r}, t) - \frac{\alpha_{1\varphi}^2}{2} S_{rr0110100}(\vec{r}, t) - \frac{z}{L} \left[\alpha_{1z} S_{tz1110210}(\vec{r}, t) \Big|_{z=-L} + S_{rr1110210}(\vec{r}, t) \Big|_{z=-L} \times \right. \\
& \times \frac{\alpha_{1r}^2}{2} - \alpha_{1z} t \varphi^2 \frac{L^2}{4} - \frac{\alpha_{1\varphi}^2}{2} S_{rr1010100}(\vec{r}, t) \Big|_{z=-L} + \frac{\alpha_{1r}^2}{2} S_{rr0110210}(\vec{r}, t) - \frac{\alpha_{1z}^2}{2} S_{rr1100100}(\vec{r}, t) \Big|_{z=-L} - \\
& - \alpha_{1z} L^2 \frac{t}{2} - \alpha_{1z}^2 \frac{L}{2} S_{zz1100200}(\vec{r}, t) \Big|_{z=-L} - \frac{\alpha_{1z}^2}{2} S_{zz1110211}(\vec{r}, t) \Big|_{z=-L} - \frac{\alpha_{1\varphi}^2}{2} S_{\varphi\varphi1010210}(\vec{r}, t) \Big|_{z=-L} \left. \right] - \\
& - \int_0^t \int_0^r (r-u) \int_0^\varphi (\varphi-v) \frac{P}{\rho} dv du d\tau \Big\} .
\end{aligned}$$

Values of parameters ai, bi and ci could be determined by the following relations

$$\begin{aligned}
 a_1 = & \frac{R^2}{4} \mu_{012r12} - \frac{1}{2} \mu_{112r01} - \frac{1}{8} \mu_{111r12} - \frac{R}{4} \mu_{112r12} + \frac{R}{4} \mu_{012r01} - \frac{L}{8} \tilde{\mu}_{211r12} - \frac{L}{4} \tilde{\mu}_{111r01} + \\
 & + L \frac{R^2}{8} \tilde{\mu}_{011r12} + L \frac{R}{4} \tilde{\mu}_{011r10} + L \frac{R}{4} \tilde{\mu}_{011r01} - L \frac{R}{4} \tilde{\mu}_{111r02ijk\rho lm} ; \quad \mu_{ijk\rho lm} = \int_0^\Theta (\Theta - t) \int_0^R (R - r)^i \times \\
 & \int_0^{2\pi} (2\pi - \phi)^j \int_{-L}^L (L - z)^k \left(\frac{\partial v}{\partial \rho} \right)^l \frac{dz}{v^m} d\phi dr dt ; \quad \tilde{\mu}_{ijk\rho lm} = \int_0^\Theta (\Theta - t) \int_0^R (R - r)^i \int_0^{2\pi} (2\pi - \phi)^j \times \\
 & \times \int_{-L}^L (L + z)^k \left(\frac{\partial v}{\partial \rho} \right)^l \frac{dz}{v^m} d\phi dr dt ; \quad a_2 = \frac{R^2}{4} \mu_{010\phi12} - \frac{1}{8} \mu_{212\phi12} - \frac{1}{2} \mu_{001\phi12} - \mu_{011\phi12} \times \\
 & \times L \frac{R}{4} - \frac{L}{4} \tilde{\mu}_{111\phi12} + L \frac{R^2}{8} \tilde{\mu}_{010\phi12} - L \frac{R}{4} \tilde{\mu}_{011\phi12} ; \quad a_3 = \frac{R^2}{4} \mu_{012z12} - R \mu_{011z01} - \frac{1}{4} \mu_{210z01} - \\
 & - \frac{1}{8} \mu_{212z12} + L \frac{R^2}{8} \tilde{\mu}_{011z12} + L \frac{R}{4} \tilde{\mu}_{010z12} + L \frac{R}{4} \mu_{010z01} ; \quad a_4 = \frac{R^2}{4} \mu_{012z01} - \frac{1}{4} \mu_{211r12} + \frac{R^2}{4} \times \\
 & \times \mu_{012r12} - \frac{1}{4} \mu_{212r01} - 8R^3 L \Theta^2 \frac{\pi^2}{3} - \frac{R}{2} \mu_{112r12} - \frac{R}{2} \mu_{112r01} - 3\Theta^2 R^2 L^2 \frac{\pi^2}{2} - \frac{L}{4} \tilde{\mu}_{211r12} - \Theta^2 \times \\
 & \times R L^3 \frac{\pi^2}{2} - \frac{L}{4} \tilde{\mu}_{211r01} + L \frac{R^2}{4} \tilde{\mu}_{011r12} - L \frac{R^2}{2} \tilde{\mu}_{011r01} + R \tilde{\mu}_{101r01} - R \frac{L}{2} \tilde{\mu}_{101r12} ; \quad a_5 = V_0^2 R \frac{L}{4} \times \\
 & \times \mu_{011r01} - V_0^2 R \frac{L^2}{4} \hat{\mu}_{010r01} + V_0^2 R \frac{L^2}{4} \mu_{010r01} + \frac{L}{2} \int_0^\Theta (\Theta - t) \int_0^{2\pi} (2\pi - \phi) \int_{-L}^0 \frac{P}{\rho} dz d\phi dt - \int_0^\Theta (\Theta - t) \times \\
 & \times \int_0^R (R - r) \int_0^{2\pi} (2\pi - \phi) \int_{-L}^L (L - z) \frac{P}{\rho} dz d\phi dt + \int_0^\Theta \int_0^R (R - r) \int_0^{2\pi} (2\pi - \phi) \int_{-L}^L (L - z) \frac{P}{\rho} dz d\phi dr \times \\
 & \times (\Theta - t) dt ; \quad \hat{\mu}_{ijk\rho lm} = \int_0^\Theta (\Theta - t) \int_0^R (R - r)^i \int_0^{2\pi} (2\pi - \phi)^j \int_0^L (L - z)^k \left(\frac{\partial v}{\partial \rho} \right)^l \frac{dz}{v^m} d\phi dr dt ; \\
 b_1 = & \frac{1}{4} \mu_{222r01} + \frac{1}{8} \mu_{322r12} - \frac{1}{4} \mu_{322r01} + \pi^2 \mu_{312r01} - \frac{\pi^2}{2} \mu_{312r12} - \pi^2 \mu_{012r01} \frac{R^3}{6} + \hat{\mu}_{211r01} \times \\
 & \times L \frac{\pi}{4} - \frac{L}{4} \hat{\mu}_{211r01} - \frac{L}{8} \hat{\mu}_{321r12} - \frac{L}{4} \left(\pi + \frac{1}{2} \right) \hat{\mu}_{321r01} + L \frac{\pi}{4} \hat{\mu}_{311r12} ; \quad b_2 = \frac{1}{2} \mu_{211r01} - \frac{1}{2} \hat{\mu}_{211r01} + \\
 & + L \frac{\pi}{4} \hat{\mu}_{201r01} - \frac{\pi^2}{2} \mu_{202r01} ; \quad b_3 = \frac{1}{4} \mu_{321z01} + \frac{1}{8} \mu_{322z12} - \pi^2 \mu_{311z01} - \frac{\pi^2}{4} \mu_{312z12} - \frac{L}{4} \mu_{320z01} -
 \end{aligned}$$

$$\begin{aligned}
& -\frac{L}{8}\mu_{321z12} + L\frac{\pi}{4}\hat{\mu}_{310z01} + L\frac{\pi}{4}\hat{\mu}_{310z12} ; \quad b_4 = -\pi^2\Theta^2R^2\frac{L^2}{4} - 2\pi^2\Theta^2RL^3 ; \quad b_5 = \frac{1}{2}\mu_{322t12} + \\
& + \frac{1}{2}\mu_{322t01} - \pi\mu_{312t01} - \pi\mu_{322t12} - 2\pi^3\Theta^2R^3L - \frac{L}{4}\hat{\mu}_{321t01} - \frac{L}{4}\hat{\mu}_{321t01} - \frac{L}{4}\hat{\mu}_{321t12} + L\frac{\pi}{2}\hat{\mu}_{311t12} + \\
& + L\frac{\pi}{2}\hat{\mu}_{311t01} ; \quad b_6 = \omega^2R^5\Theta^2L\frac{\pi^3}{10} - \int_0^\Theta(\Theta-t)\int_0^Rr(R-r)\int_{-L}^{2\pi}\int_0^L(L-z)\frac{P}{\rho}dzd\varphi drdt ; \\
& c_1 = -\frac{1}{8}\mu_{211r12} - \frac{1}{8}\mu_{211r01} - \frac{L}{8}\mu_{021r01} - \frac{L}{16}\tilde{\mu}_{221r12} ; \quad c_2 = -\frac{1}{8}\mu_{122\varphi12} - \frac{1}{8}\mu_{122\varphi01} - \\
& - \frac{L}{8}\tilde{\mu}_{211\varphi01} - \frac{L}{8}\tilde{\mu}_{211\varphi12} ; \quad c_3 = \frac{1}{8}\mu_{222z12} - \frac{1}{8}\mu_{222z01} - \frac{L^2}{16}\mu_{220z01} - \frac{1}{16}\tilde{\mu}_{220z12} - \frac{L^2}{16}\tilde{\mu}_{220z12} ; \\
& c_4 = \Theta^2R^3\frac{\pi^3}{18} ; \quad c_5 = \frac{L}{4}\tilde{\mu}_{221t12} - \frac{1}{8}\mu_{222t12} + \Theta^2RL^3\frac{\pi^3}{6} - \frac{1}{8}\mu_{221t01} - \frac{L}{8}\tilde{\mu}_{221t01} - L^3\Theta^2R\frac{\pi}{12} ; \\
& c_6 = -\int_0^\Theta(\Theta-t)\int_0^R(R-r)^2\int_0^{2\pi}(2\pi-\varphi)\int_{-L}^L\frac{P}{4\rho}dzd\varphi drdt .
\end{aligned}$$

Second-order approximations of components of velocity of flow of composition of gases (gas-carrier and materials in gas phase, which are used for formation epitaxial layer) v_r , v_φ and v_z could be written as

$$\begin{aligned}
v_{2r} = & \alpha_{2r} + v_{1r} + \left\{ \int_0^t \int_0^R \int_0^\varphi (\varphi - v) \int_0^z (\alpha_{2r} + v_{1r}) dw dv du d\tau + \int_0^t \int_0^R \int_0^\varphi (\alpha_{2r} + v_{1r}) dw dv du d\tau + \right. \\
& + \int_0^t \int_0^R \int_0^\varphi (\alpha_{2z} + v_{1z}) dw dv du d\tau - \int_0^t \int_0^R (r-u) \int_0^\varphi (\alpha_{2r} + v_{1r}) dv du d\tau - \int_0^r (r-u) \int_0^\varphi (\alpha_{2r} + v_{1r}) \times \\
& \times (z-w) \frac{dw}{v} dv du - \int_0^r (r-u) \int_0^\varphi \int_0^z (z-w) (\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w) \times \\
& \times (\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R (r-u) \int_0^\varphi \int_0^z (\alpha_{2z} + v_{1z}) \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R (r-u) \int_0^\varphi \int_0^z (z-w) \\
& - w) (\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R \frac{r-u}{u} \int_0^\varphi \int_0^z (z-w) (\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv du d\tau + \\
& + r \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w) (\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau + \int_0^R r \int_0^\varphi \int_0^z (z-w) (\alpha_{2r} + v_{1r}) \frac{dw}{v} dv dr - \\
& - \int_0^t \int_0^R \int_0^\varphi \int_0^z (\alpha_{2r} + v_{1r}) dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^R (r-u) \int_0^\varphi \int_0^z (z-w) (\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau + \\
& + \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w) (\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau + \int_0^t \int_0^R r \int_0^\varphi (\alpha_{2r} + v_{1r}) dv dr d\tau - \int_0^t \int_0^R (R-u) \times
\end{aligned}$$

$$\begin{aligned}
 & \times \int_0^\varphi (\alpha_{2r} + v_{1r}) dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^z (\alpha_{2z} + v_{1z}) dw dv du d\tau - \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2r} + v_{1r}) \frac{dw}{v} dv \times \\
 & \times u du + \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \times \\
 & \times \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau + \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \times \\
 & \times \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^z (\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{2v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^z (\alpha_{2z} + v_{1z})^2 \frac{dw}{2v} dv du d\tau - \\
 & - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv du d\tau + \int_0^t \int_0^R \int_0^\varphi \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{2v} dv du d\tau - \\
 & - R \int_0^t \int_0^R \int_0^\varphi (\alpha_{2r} + v_{1r}) dv du d\tau - \frac{z}{L} \left[\int_0^r (r-u) \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r}) \frac{dw}{v} dv du + \int_0^t \int_0^r (r-u) \times \right. \\
 & \times \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau + \int_0^t \int_0^r \int_0^\varphi \int_0^0 (\alpha_{2r} + v_{1r}) dw dv du d\tau + \frac{1}{2} \int_0^t \int_0^r (r-u) \times \\
 & \times \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau + \frac{1}{2} \int_0^t \int_0^r \int_0^\varphi \int_0^0 (L+w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv \times \\
 & \times \frac{r-u}{u} du d\tau + \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2z} + v_{1z}) dw dv du d\tau + \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r}) \frac{dw}{2v} dv du d\tau + \\
 & + \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (z-w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv du d\tau - \frac{V_0^2}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 \frac{dw}{v} dv du d\tau - r \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w) \times \\
 & \times (\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau - \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv du d\tau - \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w) \times \\
 & \times (\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r}) dw dv d\tau - r \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2r} + v_{1r}) (L + \\
 & + w) \frac{dw}{v} dv du - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv du d\tau - \frac{r}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w)(\alpha_{2z} + v_{1z})^2 \times \\
 & \times \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2r} + v_{1r}) dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau + \\
 & + \int_0^t \int_0^R \int_0^\varphi \int_0^0 (L+w)(\alpha_{2r} + v_{1r}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_0^0 (\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau +
 \end{aligned}$$

$$\begin{aligned}
& + \int_0^R u \int_0^\varphi \int_{-L}^0 (L+w) \frac{v_r}{v} dw dv du - \int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 (\alpha_{2z} + v_{1z}) dw dv du d\tau + \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 (\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} (L + \\
& \quad + w) \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 \frac{P}{\rho} dw dv d\tau \left\} \frac{v}{2RL}, \\
& v_{2\varphi} = \alpha_{2\varphi} + v_{1\varphi} + \frac{v}{2LR} \left(\int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 (z-w)(\alpha_{2r} + v_{1r}) dw dv du d\tau - r \int_0^t \int_0^\varphi \int_{-L}^0 (\alpha_{2r} + v_{1r})(z - \right. \\
& \quad - w) dw dv d\tau + \int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 (\alpha_{2r} + v_{1r}) dw dv du d\tau - \int_0^t \int_0^R u \int_0^\varphi (\varphi - v)(\alpha_{2\varphi} + v_{1\varphi}) dv du d\tau + \\
& \quad + \int_0^r u^2 \int_0^\varphi (\varphi - v) \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v} dv du + \frac{r^2}{2} \int_0^t \int_0^\varphi (\varphi - v) \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \times \\
& \quad \times \frac{dw}{v} dv d\tau + \int_0^t \int_0^R u^2 \int_0^\varphi (\varphi - v) \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^R u^2 \int_0^\varphi (\varphi - v) \times \\
& \quad \times \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{dv}{v} du d\tau + \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi (\varphi - v) \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv \times \\
& \quad \times u^2 du d\tau + \frac{1}{2} \int_0^t \int_0^R u^2 \int_0^\varphi (\varphi - v) \int_0^z (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dw dv du d\tau + \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi \int_{-L}^0 (\alpha_{2\varphi} + v_{1\varphi})^2 \times \\
& \quad \times (z-w) \frac{dw}{v} dv du d\tau + \frac{1}{2} \int_0^t \int_0^R \int_0^\varphi u^2 \int_0^z (\varphi - v) \int_0^z (z-w)(\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau + \\
& \quad + \frac{\varphi}{2\pi} \left[r \int_0^t \int_0^R \int_0^{2\pi} \int_{-L}^0 (z-w)(\alpha_{2r} + v_{1r}) dw dv d\tau - \int_0^t \int_0^R \int_0^{2\pi} \int_{-L}^0 (\alpha_{2r} + v_{1r}) dw dv du d\tau - \int_0^t \int_0^R \int_0^{2\pi} \int_{-L}^0 (z - \right. \\
& \quad - w)(\alpha_{2r} + v_{1r}) dw du d\tau - \frac{r^2}{2} \int_0^t \int_0^{2\pi} (2\pi - v) \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv d\tau - \int_0^r u^2 \times \\
& \quad \times \int_0^{2\pi} (2\pi - v) \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v} dv du - \int_0^t \int_0^R u^2 \int_0^{2\pi} (2\pi - v) \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v^2} \times \\
& \quad \times \frac{\partial v}{\partial \tau} dv du d\tau + \int_0^t \int_0^R u \int_0^{2\pi} (2\pi - v)(\alpha_{2\varphi} + v_{1\varphi}) dv du d\tau + \int_0^t \int_0^R u^2 \int_0^{2\pi} (2\pi - v) \int_0^z (\alpha_{2r} + v_{1r})^2 (z - \\
& \quad - w) \frac{dw}{v} dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^R u^2 \int_0^{2\pi} (2\pi - v) \int_0^z (z-w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau - \\
& \quad - \frac{1}{2} \int_0^t \int_0^R u^2 \int_0^{2\pi} (2\pi - v) \int_0^z (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^R u^2 \int_0^{2\pi} (2\pi - v) \int_0^z (z-w)(\alpha_{2z} + v_{1z})^2 \times \\
& \quad \times \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau - \left. \frac{1}{2} \int_0^t \int_0^R u \int_0^{2\pi} \int_0^z (z-w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{dw}{v} dv du d\tau \right] - (2\pi - \varphi) \omega^2 r^4 t \frac{\varphi}{4} +
\end{aligned}$$

$$\begin{aligned}
& + \frac{z}{L} \left\{ r \int_0^t \int_0^r \int_0^\varphi \int_0^L (L-w)(\alpha_{2r} + v_{1r}) dw dv d\tau - \int_0^t \int_0^r \int_0^\varphi \int_0^L (L-w)(\alpha_{2r} + v_{1r}) dw dv du d\tau - \frac{r^2}{2} \int_0^t \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv d\tau \right. \\
& - \int_0^r u^2 \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v} dv du - \int_0^r u^2 \times \\
& \times \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v} dv du - \int_0^t \int_0^r \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv \times \\
& \times u^2 du d\tau - \frac{1}{2} \int_0^t \int_0^r u^2 \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau - \int_0^t \int_0^r u^2 \int_0^\varphi (\varphi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv du d\tau \\
& - \int_0^t \int_0^r \int_0^\varphi (\alpha_{2r} + v_{1r}) dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^r \int_0^\varphi (\varphi - v) \int_0^L (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^r u^2 \int_0^\varphi (\varphi - v) \int_0^L (\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau \\
& - \frac{1}{2} \int_0^t \int_0^r u \int_0^\varphi \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{dw}{v} dv du d\tau - \frac{\varphi}{2\pi} \left[r \int_0^t \int_0^r \int_0^\varphi \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 dw dv d\tau \right. \\
& - \frac{r^2}{2} \int_0^t \int_0^\varphi (2\pi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv d\tau - \int_0^t \int_0^r \int_0^\varphi \int_0^L (L-w)(\alpha_{2r} + v_{1r}) dw dv du d\tau \\
& - \int_0^t \int_0^r \int_0^\varphi (\alpha_{2r} + v_{1r}) dw dv du d\tau - \int_0^t \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau \\
& - \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi}) \frac{dw}{v} dv du - \frac{1}{2} \int_0^t \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \times \\
& \times \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau + \int_0^t \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (L-w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau \\
& - \frac{1}{2} \int_0^t \int_0^r u^2 \int_0^\varphi (2\pi - v) \int_0^L (\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau - \\
& \left. - \frac{1}{2} \int_0^t \int_0^r u \int_0^\varphi \int_0^L (L-w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{dw}{v} dv du d\tau \right] + \omega^2 t r^4 (2\pi - \varphi) \frac{\varphi}{4} \left\{ - \int_0^t \int_0^r \int_0^\varphi \frac{P}{\rho} dw du d\tau \right\}, \\
v_{2z} &= \alpha_{2z} + v_{1z} + \frac{v}{2RL} \left\{ \int_0^t \int_0^r (r-u) \int_0^\varphi (\varphi - v)(\alpha_{2r} + v_{1r}) dv du d\tau + \int_0^t \int_0^\varphi (\varphi - v) \int_0^z (\alpha_{2z} + v_{1z})(z-w) dw dv du d\tau \right. \\
& \left. + \int_0^t \int_0^r \frac{r-u}{u^2} \int_0^\varphi \int_0^z (z-w)(\alpha_{2z} + v_{1z}) dw dv du d\tau - \frac{1}{2} \int_0^t \int_0^r (r-u) \int_0^\varphi (\varphi - v) \int_0^z (z-w) dw dv du d\tau \right\},
\end{aligned}$$

$$\begin{aligned}
& -w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \frac{dw}{v^2} dv du d\tau - \frac{1}{2} \int_0^t \int_0^r \int_0^\varphi (\varphi - v) \int_0^z (z - w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv \times \\
& \times \frac{1}{u} du d\tau - \frac{1}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_0^z (z - w)(\alpha_{2r} + v_{1r})^2 \frac{dw}{v} dv du d\tau - \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \times \\
& \times \int_0^z (z - w)(\alpha_{2z} + v_{1z}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau - \frac{1}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_0^z (z - w)(\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \times \\
& \times \frac{dw}{v^2} dv du d\tau - \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_0^z (z - w)(\alpha_{2z} + v_{1z}) \frac{dw}{v} dv du - \frac{1}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \times \\
& \times \int_0^z (z - w)(\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau - \frac{1}{2} \int_0^t \int_0^r \int_0^\varphi (\varphi - v) \int_0^z (z - w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{dw}{v} dv \times \\
& \times \frac{1}{u} du d\tau - \frac{z}{L} \left[\int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_{-L}^0 (L + w)(\alpha_{2z} + v_{1z}) \frac{dw}{v} dv du - \int_0^t \int_0^r (\varphi - v) \int_{-L}^0 (L + w) \times \right. \\
& \times (\alpha_{2z} + v_{1z}) dw dv d\tau + \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_{-L}^0 (L + w)(\alpha_{2z} + v_{1z}) \frac{\partial v}{\partial \tau} \frac{dw}{v^2} dv du d\tau + \\
& + \frac{1}{2} \int_0^t \int_0^\varphi (\varphi - v) \int_{-L}^0 (L + w) \frac{v_r^2}{v} dw dv d\tau + \frac{1}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_{-L}^0 (L + w)(\alpha_{2r} + v_{1r})^2 \frac{\partial v}{\partial u} \times \\
& \times \frac{dw}{v^2} dv du d\tau + \int_0^t \int_0^r \frac{(r - u)}{2u} \int_0^\varphi \int_{-L}^0 (L + w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{dw}{v} dv du d\tau + \frac{1}{2} \int_0^t \int_0^r (r - u) \times \\
& \times \int_0^\varphi (\varphi - v) \int_{-L}^0 (\alpha_{2z} + v_{1z})^2 \frac{dw}{v} dv du d\tau - \int_0^t \int_0^r \frac{(r - u)}{u^2} \int_{-L}^0 (L + w)(\alpha_{2z} + v_{1z}) dw du d\tau + \\
& + \frac{1}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_{-L}^0 w(\alpha_{2z} + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau + \frac{L}{2} \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \int_{-L}^0 (\alpha_{2z} + \\
& + v_{1z})^2 \frac{\partial v}{\partial w} \frac{dw}{v^2} dv du d\tau + \frac{1}{2} \int_0^t \int_0^r \frac{r - u}{u} \int_0^\varphi \int_{-L}^0 (L + w)(\alpha_{2\varphi} + v_{1\varphi})^2 \frac{\partial v}{\partial v} \frac{dw}{v^2} dv du d\tau \Big] - \\
& \left. - \int_0^t \int_0^r (r - u) \int_0^\varphi (\varphi - v) \frac{P}{\rho} dv du d\tau \right\}.
\end{aligned}$$

Values of parameters A_i , B_i and C_i could be determined by the following relations

$$\begin{aligned}
A_1 = & \frac{R^2}{8} \mu_{012r12} - \frac{R}{4} \mu_{112r12} - \frac{1}{4} \mu_{112r01} - \frac{1}{8} \mu_{212r12} + \frac{R}{4} \mu_{012r01} - \frac{L}{8} \tilde{\mu}_{211r12} + L \frac{R^2}{8} \tilde{\mu}_{011r01} + L \frac{R}{4} \times \\
& \times \tilde{\mu}_{011r01} + L \frac{R}{4} \tilde{\mu}_{011r01} - L \frac{R}{4} \tilde{\mu}_{111r12}; \quad A_2 = \frac{R^2}{4} \mu_{011\varphi12} - \frac{1}{4} \mu_{212\varphi12} - \frac{R}{4} \mu_{012\varphi12} - \frac{L}{8} \tilde{\mu}_{211\varphi12} -
\end{aligned}$$

$$\begin{aligned}
& -L \frac{R}{4} \tilde{\mu}_{011\varphi 12} + L \frac{R^2}{8} \tilde{\mu}_{010\varphi 12} + \frac{R}{2} \tilde{\mu}_{011\varphi 12} ; A_3 = \frac{R}{4} \mu_{012z12} - \frac{1}{4} \mu_{212z12} - \frac{R}{2} \mu_{011z01} + \tilde{\mu}_{010z12} \times \\
& \times L \frac{R}{4} - \frac{R}{2} \mu_{011z12} - \frac{R^2}{4} \tilde{\mu}_{011z12} - \frac{R}{2} \tilde{\mu}_{010z01} ; A_4 = \frac{R^2}{4} \Omega_{0121rr121} - \frac{R}{2} \mu_{112r01} - \frac{R}{2} \mu_{112t12} - \frac{R}{2} \times \\
& \times \Omega_{1121rr121} - \frac{1}{8} \mu_{222r01} - \frac{1}{8} \mu_{212r01} - \frac{1}{4} \mu_{212t10} - \frac{1}{2} \Omega_{212rr011} + \frac{R^2}{4} \mu_{012t12} - \frac{1}{2} \Omega_{212rr1121} - \tilde{\mu}_{211\kappa 12} \times \\
& \times \frac{L}{8} - \Theta^2 L R^3 \frac{\pi}{3} + \frac{R}{2} \Omega_{012rr1011} + \Theta^2 R^2 L^2 \frac{\pi^2}{2} - \frac{L}{4} \tilde{\mu}_{211r01} - \frac{L}{4} \tilde{\mu}_{211t12} - \frac{L}{4} \tilde{\Omega}_{211rr1121} - \frac{7}{2} \pi^2 \Theta^2 \times \\
& \times R^3 L - \frac{L}{4} \tilde{\mu}_{211r01} + L \frac{R^2}{4} \tilde{\mu}_{011t12} + L \frac{R^2}{4} \tilde{\Omega}_{011rr1121} + L \frac{R^2}{4} \tilde{\mu}_{011r01} + L \frac{R}{2} \tilde{\Omega}_{011rr1011} - R \frac{L}{2} \tilde{\mu}_{111r01} + \\
& + R \frac{L}{2} \tilde{\Omega}_{011rr1011} - L \frac{R}{2} \tilde{\Omega}_{111rr1121} ; \Omega_{ijk\rho lmno} = \int_0^\Theta (\Theta - t) \int_0^R \int_0^{2\pi} (2\pi - \varphi)^j \int_{-L}^L (L - z)^k (v_{lp})^o \left(\frac{\partial v}{\partial \lambda} \right)^m \frac{dz}{v^n} d\varphi \times \\
& \times (R - r)^i dr dt ; \tilde{\Omega}_{ijk\rho lmno} = \int_0^\Theta (\Theta - t) \int_0^R (R - r)^i \int_0^{2\pi} (2\pi - \varphi)^j \int_{-L}^L (L - z)^k (v_{lp})^o \left(\frac{\partial v}{\partial \lambda} \right)^m \frac{dz}{v^n} d\varphi dr dt ; \\
& A_5 = \frac{R^2}{2} \Omega_{012\varphi\varphi 1121} - \frac{1}{4} \Omega_{212\varphi\varphi 1121} - \frac{R}{2} \Omega_{012\varphi\varphi 1121} - \frac{L}{4} \Omega_{211\varphi\varphi 1121} - R \frac{L}{2} \Omega_{011\varphi\varphi 1121} + \Omega_{010\varphi\varphi 1121} \times \\
& \times L \frac{R^2}{4} - \frac{L}{2} R \tilde{\mu}_{111t12} + R \tilde{\Omega}_{011\varphi\varphi 1121} ; A_6 = \frac{R^2}{4} \Omega_{012z 1121} - \frac{1}{4} \Omega_{212z 1121} - \frac{1}{4} \mu_{210z0} - \Omega_{010z 1011} \times \\
& \times R + \pi^2 \Theta^2 R^2 L^2 + L \frac{R^2}{4} \tilde{\Omega}_{011z 1121} - R \tilde{\Omega}_{011z 1121} + R \frac{L}{2} \tilde{\Omega}_{010z 1011} + L \frac{R}{2} \tilde{\Omega}_{010z 1121} ; A_7 = \\
& = \frac{1}{2} \Omega_{210rr1001} - \frac{1}{2} \Omega_{121rr1001} - \frac{1}{4} \Omega_{212tr1101} - \Omega_{221zz1001} + \frac{1}{4} \Omega_{212rr1011} + \frac{1}{4} \Omega_{212rr1012} + \frac{1}{4} \Omega_{211zz1011} - \\
& - \frac{1}{8} \Omega_{212rr2122} - \frac{1}{8} \Omega_{212\varphi\varphi 2122} - R \Omega_{110rr1001} - \frac{1}{8} \Omega_{212zz2122} + \frac{1}{2} \Omega_{112rr1011} - R \Omega_{011rr1001} + \Omega_{012rr1122} \times \\
& \times \frac{R^2}{8} - \frac{R^2}{4} \Omega_{012rt 1121} + R \Omega_{110rr1001} + R \Omega_{011zz1001} + \frac{R}{2} \Omega_{112rr1011} - \frac{R^2}{8} \Omega_{012zz1122} + \frac{R}{4} \Omega_{112rt1121} + \\
& + \frac{R}{4} \Omega_{112rr1122} - \frac{R^2}{4} \Omega_{0121\varphi\varphi 1122} + \frac{R}{4} \Omega_{012\varphi\varphi 1122} + \frac{R}{2} \Omega_{011zz1012} - \frac{R}{4} \Omega_{012rr1012} - \frac{R}{4} \Omega_{012rr1012} + \frac{R}{2} \times \\
& \times \Omega_{011zz1122} + R^2 L \Omega_{010rr1001} - \frac{L}{4} \tilde{\Omega}_{211rr1011} - \frac{L}{4} \tilde{\Omega}_{211rr1121} - \frac{L}{4} \tilde{\Omega}_{110rr1001} - \frac{L}{8} \tilde{\Omega}_{211rr1122} - \frac{L}{2} \times
\end{aligned}$$

$$\begin{aligned}
& \times \tilde{\Omega}_{110zz1001} - \frac{L}{4} \tilde{\Omega}_{111rr1011} - \frac{L}{2} \tilde{\Omega}_{211\varphi\varphi1122} + V_0^2 L \frac{R}{4} \tilde{\mu}_{010r01} - L \frac{R}{4} \tilde{\Omega}_{011\varphi\varphi1122} + L \tilde{\Omega}_{011rt1121} \frac{R^2}{4} + \\
& + L \frac{R^2}{8} \tilde{\Omega}_{011rr1122} + L \frac{R^2}{8} \tilde{\Omega}_{010\varphi\varphi1122} + L \frac{R^2}{4} \tilde{\Omega}_{011rr1011} + \frac{L}{2} \tilde{\Omega}_{011rr1001} + L \frac{R}{4} \tilde{\Omega}_{011rr1012} - R \frac{L}{2} \times \\
& \times \tilde{\Omega}_{111rr1011} + R \frac{L}{2} \tilde{\Omega}_{010rr1001} + L \frac{R}{4} \tilde{\Omega}_{011rr1012} + L \frac{R^2}{8} \tilde{\Omega}_{011zz1122} - R \frac{L}{2} \tilde{\Omega}_{111rt1121} + R \frac{L}{2} \tilde{\Omega}_{010zz1001} + \\
& + L \frac{R}{4} \tilde{\Omega}_{010zz1012} - L \frac{R}{4} \tilde{\Omega}_{011\varphi\varphi1121} + L \frac{R}{4} \tilde{\Omega}_{010zz1122} - L \frac{R}{4} \tilde{\Omega}_{111rr1122} - L \frac{R}{2} \int_0^\Theta (\Theta - t) \int_0^{2\pi} (2\pi - \varphi) \times \\
& \times \int_{-L}^0 \frac{P}{\rho} dz d\varphi dt + \int_0^\Theta (\Theta - t) \int_0^R (R - r) \int_0^{2\pi} (2\pi - \varphi) \int_{-L}^L (L - z) \frac{P}{\rho} dz d\varphi du dt \quad B_1 = \frac{1}{8} \mu_{222r01} - \\
& - \frac{1}{2} \mu_{322r01} + \frac{1}{4} \mu_{322r12} - \frac{\pi}{4} \mu_{212r01} + \frac{\pi}{2} \mu_{312r01} - \frac{\pi}{4} \mu_{312r12} - \frac{L}{8} \mu_{221r01} - \frac{L}{8} \hat{\mu}_{321r12} + \frac{\pi^2}{8} \times \\
& \times \Theta^2 R^2 L^3 - \hat{\mu}_{321r01} \frac{L}{4} + L \frac{\pi}{4} \hat{\mu}_{211r01} + L \frac{\pi}{4} \hat{\mu}_{311r12} - \pi \frac{L}{2} \hat{\mu}_{211r01} \quad B_2 = \frac{1}{2} \mu_{222r01} + L \frac{\pi}{4} \times \\
& \times \hat{\mu}_{201r01} - \frac{\pi}{2} \mu_{202r01} - \frac{L}{4} \hat{\mu}_{ijk\varphi lm} \mu_{211r01} \quad B_3 = \frac{1}{4} \mu_{321r01} + \frac{1}{8} \mu_{322z12} - \frac{\pi}{2} \mu_{311z01} - \frac{\pi}{4} \mu_{312z12} - \\
& - \frac{L}{8} \mu_{121z12} - \frac{L}{8} \mu_{320z01} + L \frac{\pi}{4} - \frac{\pi}{4} \mu_{310z01} + L \frac{\pi}{4} - \frac{\pi}{4} \mu_{310z12} \quad B_4 = \frac{1}{4} \Omega_{202rr1011} - \Theta^2 R^2 L^2 \times \\
& \times \frac{\pi^2}{4} - \frac{1}{2} \Omega_{322rr1011} + \frac{1}{4} \Omega_{322rr1121} - \frac{\pi}{2} \Omega_{212rr1011} + \pi \Omega_{312rr1011} - \frac{\pi}{2} \Omega_{312rr1121} - \frac{L}{4} \Omega_{221rr1011} - \\
& - \frac{L}{4} \hat{\Omega}_{321rr1121} - \frac{L}{2} \hat{\Omega}_{321rr1011} + \pi \frac{L}{2} \hat{\mu}_{211r01} - \pi L \hat{\Omega}_{101rr1001} + \pi \frac{L}{2} \hat{\Omega}_{311rr1121} + \pi L \hat{\Omega}_{211rr1011} \quad ; \\
& B_5 = \frac{1}{4} \mu_{322r01} + \frac{1}{4} \mu_{322t12} + \frac{1}{4} \mu_{322t12} + \frac{1}{2} \Omega_{212\varphi\varphi1011} - \frac{\pi}{2} \mu_{312r01} - \frac{\pi}{2} \Omega_{202\varphi\varphi1011} - \frac{1}{2} \mu_{312t12} + \Theta^2 \frac{\pi^3}{3} R^3 L - \\
& - \frac{L}{4} \mu_{321t01} - \frac{L}{4} \hat{\mu}_{321r01} - \frac{L}{4} \hat{\mu}_{321t12} - \frac{L}{2} \hat{\mu}_{211\varphi01} + L \frac{\pi}{2} \hat{\mu}_{211t12} + L \frac{\pi}{2} \hat{\mu}_{311r01} + L \frac{\pi}{2} \hat{\mu}_{201\varphi01} \quad B_6 = \\
& = \frac{1}{2} \Omega_{321zz1011} + \frac{1}{4} \Omega_{322zz1121} - \pi \Omega_{311zz1011} - \pi \Omega_{312zz1121} - \frac{L}{4} \Omega_{321zz1011} - \frac{L}{4} \hat{\Omega}_{321zz1121} - \hat{\Omega}_{321zz1121} \times \\
& \times \pi \frac{L}{2} - \pi \frac{L}{2} \hat{\Omega}_{310zz1011} \quad B_7 = \frac{1}{2} \Omega_{112rr1001} - \Omega_{212rr1001} - \Omega_{111rr1001} + \frac{1}{2} \Omega_{220\varphi\varphi1001} - \\
& - \frac{1}{4} \Omega_{322\varphi\varphi1011} - \frac{1}{8} \Omega_{222rr1012} - \frac{1}{2} \Omega_{322\varphi\varphi1121} - \frac{1}{8} \Omega_{322rr1122} + \frac{1}{4} \Omega_{322rr1012} - \frac{1}{4} \Omega_{321zz1012} -
\end{aligned}$$

$$\begin{aligned}
& -\frac{1}{4}\Omega_{212\varphi\varphi 1012} - \frac{1}{8}\Omega_{322zz1122} + \frac{\pi}{2}\Omega_{002rr1001} + \pi\Omega_{101rr1001} - \frac{\pi}{2}\Omega_{102rr1001} + \frac{\pi}{4}\Omega_{212rr1012} + \\
& + \frac{\pi}{2}\Omega_{312\varphi\varphi 1011} + \frac{\pi}{2}\Omega_{312\varphi t1121} - \pi\Omega_{210\varphi\varphi 1001} - \frac{\pi}{2}\Omega_{312rr1012} + \frac{\pi}{4}\Omega_{312rr1122} + \frac{\pi}{2}\Omega_{311zz1012} + \\
& + \frac{\pi}{4}\Omega_{312zz1122} - \frac{L}{2}\Omega_{111rr1001} + \frac{L}{2}\Omega_{111rr1001} + \frac{L}{8}\Omega_{221rr1012} + \frac{L}{8}\hat{\Omega}_{321rr1122} + \frac{L}{4}\hat{\Omega}_{321\varphi\varphi 1011} + \frac{L}{4} \times \\
& \times \hat{\Omega}_{321\varphi\varphi 1011} + \frac{L}{4}\hat{\Omega}_{321\varphi t1121} - \omega^2 LR^5 \Theta^2 \frac{\pi^2}{20} + \frac{L}{4}\hat{\Omega}_{321rr1012} + \frac{L}{4}\hat{\Omega}_{312zz1012} + \frac{L}{2}\hat{\Omega}_{110rr1001} + \\
& + \frac{L}{8}\hat{\Omega}_{321zz1122} + \frac{L}{4}\hat{\Omega}_{211\varphi\varphi 1012} + L\frac{\pi}{2}\hat{\Omega}_{101rr1002} - L\frac{\pi}{4}\hat{\Omega}_{011rr2012} - L\frac{\pi}{2}\hat{\Omega}_{101rr1011} - \hat{\Omega}_{100rr1001} \times \\
& \times \frac{\pi}{2}L - L\frac{\pi}{2}\hat{\Omega}_{311\varphi t1121} - \pi\frac{L}{2}\hat{\Omega}_{311\varphi\varphi 1011} - L\frac{\pi}{4}\hat{\Omega}_{311rr1122} + \pi\frac{L}{2}\hat{\Omega}_{311rr1012} - L\frac{\pi}{4}\hat{\Omega}_{310zz1012} - \\
& - L\frac{\pi}{4}\hat{\Omega}_{310zz1122} - L\frac{\pi}{4}\hat{\Omega}_{201\varphi\varphi 1012} - \int_0^\Theta (\Theta - t) \int_0^R (R - r) \int_0^{2\pi} (2\pi - \varphi) \int_{-L}^L (L - z) \frac{P}{\rho} dz d\varphi dr dt + \\
& + \omega^2 R^5 L \Theta^2 \frac{\pi^2}{40}, \quad C_1 = -\frac{1}{16}\mu_{222r12} - \frac{1}{16}\mu_{222r01} - \frac{L}{8}\tilde{\mu}_{021r01} - \frac{L}{16}\tilde{\mu}_{221r12}, \quad C_2 = \frac{1}{8}\mu_{122\varphi 12} + \\
& + \frac{1}{4}\mu_{122z01} - \frac{L}{16}\tilde{\mu}_{221z01} - \frac{L}{16}\tilde{\mu}_{221z12} - \frac{L}{8}\tilde{\mu}_{211z\varphi 1} - \frac{L}{8}\tilde{\mu}_{221\varphi 12}, \quad C_3 = -\frac{1}{16}\mu_{222z12} - \frac{1}{16}\mu_{222z01} - \\
& - \frac{L^2}{18}\tilde{\mu}_{220z12}, \quad C_4 = 2L\Theta^2 R^2 \frac{\pi^3}{9} - \frac{1}{16}\Omega_{222rr1121} - \frac{1}{8}\Omega_{222rr1011} - \frac{L}{16}\tilde{\mu}_{221rr1121} - \frac{L}{4}\tilde{\Omega}_{021rr1011}, \\
& C_5 = -\frac{1}{4}\Omega_{122\varphi\varphi 1121} - \frac{1}{4}\Omega_{222\varphi\varphi 1011} + \frac{L}{4}\tilde{\Omega}_{211\varphi\varphi 1011} - \frac{L}{4}\tilde{\Omega}_{211\varphi\varphi 1121}, \quad C_6 = 17R\Theta^2 L^3 \frac{\pi^3}{9} - \\
& - \frac{1}{8}\mu_{222t12} - \frac{1}{8}\Omega_{222zz1121} - \frac{1}{8}\mu_{222t01} - \frac{1}{8}\Omega_{222zz1011} - \frac{L}{8}\tilde{\mu}_{221t01} - \frac{L}{8}\tilde{\mu}_{221t12} - \frac{L}{8}\tilde{\mu}_{220z01} + \pi L^3 \times \\
& \times R^3 \frac{\Theta^2}{48} - \frac{L}{8}\tilde{\Omega}_{221zz1121} - \frac{L^2}{8}\tilde{\Omega}_{220zz1121}, \quad C_7 = \frac{1}{16}\Omega_{222rr1122} + \frac{1}{16}\Omega_{222rr1012} + \frac{1}{4}\Omega_{221rr1001} + \\
& + \frac{1}{4}\Omega_{022zz1001} + \frac{1}{4}\Omega_{212zz1001} + \frac{1}{4}\Omega_{122zt1121} + \frac{1}{8}\Omega_{122\varphi\varphi 1122} + \frac{1}{16}\Omega_{222zz1122} + \frac{1}{8}\Omega_{122zz1011} + \frac{1}{16} \times \\
& \times \Omega_{222zz1012} + \frac{1}{8}\Omega_{122\varphi\varphi 1012} + \frac{1}{4}\tilde{\Omega}_{221zz1011} - \frac{L}{4}\tilde{\Omega}_{021zz1001} + \frac{L}{8}\tilde{\Omega}_{221zt1121} + \frac{L}{8}\tilde{\Omega}_{021rr1012} + \frac{L}{16} \times \\
& \times \tilde{\Omega}_{221rr1122} + \frac{L}{8}\tilde{\Omega}_{211\varphi\varphi 1012} + \frac{L}{16}\tilde{\Omega}_{220zz1012} - \frac{L}{4}\tilde{\Omega}_{201zz1001} + \frac{L}{16}\tilde{\Omega}_{221zz1122} + \frac{L^2}{16}\tilde{\Omega}_{220zz1122} -
\end{aligned}$$

$$-\frac{L}{8}\tilde{\Omega}_{212\varphi\varphi 1122} + \frac{1}{2}\int_0^{\Theta}(\Theta-t)\int_0^R(R-r)^2\int_0^{2\pi}(2\pi-\varphi)^2\int_{-L}^L\frac{P}{\rho}dzd\varphi drdt$$

REFERENCES

- [1] I.P. Stepanenko. *Basis of microelectronics*. Moscow, Soviet radio (in Russian), 1980.
- [2] V.G. Gusev, Yu.M. Gusev. *Electronics*. Moscow, Higher School (in Russian), 1991.
- [3] V.I. Lachin, N.S. Savelov. *Electronics*. Rostov-on-Don, Phenics, 2001.
- [4] A.A. Vorob'ev, V.V. Korabl'ev, S.Yu. Karpov. *Semiconductors*. Vol. 37 (7). P. 98 (2003).
- [5] L.M. Sorokin, N.V. Veselov, M.P. Shcheglov, A.E. Kalmykov, A.A. Sitnikova, N.A. Feoktistov, A.V. Osipov, S.A. Kukushkin. *Technical Physics Letters*. Vol. 34 (22). P. 68 (2008).
- [6] V.V. Lundin, A.V. Sakharov, E.E. Zavarin, M.A. Sinitsin, A.E. Nikolaev, G.A. Mikhailovsky, P.N. Brunkov, V.V. Goncharov, B.Ya. Ber, D.Yu. Kazantsev, A.F. Tsatsul'nikov. *Semiconductors*. Vol. 43 (7). P. 996 (2009).
- [7] Y. Li, L.E. Antonuk, Y. El-Mohri, Q. Zhao, H. Du, A. Sawant, Yi Wang. *J. Appl. Phys.* Vol. 99 (6). P. 064501 (2006).
- [8] Chakraborty, H. Xing, M.D. Craven, S. Keller, T. Mates, J. S. Speck, S.P. Den Baars, U.K. Mishra. *J. Appl. Phys.* Vol. 96 (8). P. 4494 (2004).
- [9] M. Mitsuhashi, M. Ogasawara, H. Sugiura. *J. Cryst. Growth*. Vol. 183. P. 38 (1998).
- [10] R.A. Talalaev, E.V. Yakovleva, S.Yu. Karpova, Yu.N. Makarov. *J. Cryst. Growth*. Vol. 230. P. 232 (2001).
- [11] H.S. Carslaw, J.C. Jaeger. *Conduction of heat in solids*. - Oxford: At the Clarendon Press. 1964. 488 p.
- [12] Yu.D. Sokolov. *Applied Mechanics*. Vol.1 (1). P. 23-35 (1955).
- [13] E.L. Pankratov. *J. Comp. Theor. Nanoscience*. Vol.9 (1). P. 41-49 (2012).
- [14] E.L. Pankratov, E.A. Bulaeva. *Nanoscience and Nanotechnology Letters*. Vol. 5 (3). P. 418-426 (2013).
- [15] E.L. Pankratov, E.A. Bulaeva. *J. Adv. Phys.* Vol. 2 (1). P. 75-84 (2013).
- [16] G. Korn, T. Korn. *Mathematical Handbook for scientists and engineers. Definitions, theorems and formulas for reference and review*. Second edition. McGraw-Hill Book Company. New York, 1968.
- [17] E.L. Pankratov, E.A. Bulaeva. *Reviews in Theoretical Science*. Vol. 1 (3). P. 305-316 (2013).