About Manufacturing More Compact Bipolar Heterotransistors

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Abstract In the present paper we introduce an approach to manufacture more compact bipolar heterotransistor in all directions: in the direction, which perpendicular to series of p-n-junctions in the heterotransistor, and into all another directions.

Keywords Bipolar Heterotransistor; Optimization of Technological Process; Decreasing of Dimensions of Transistor; Analytical Approach to Model of Technological Process

1. Introduction

In the present time one of the actual questions of is increasing of density of elements of integrated circuits (*p-n*-junctions, transistors, etc.) [1-6]. It is also attracted an interest manufacturing more thin integrated circuits [1,5]. One of approaches to solve the questions is increasing of sharpness of diffusive-junction and implanted-junction rectifiers (both single rectifiers and rectifiers in their systems: transistors, thyristors, etc.), using epitaxial layers with smaller thickness in epitaxial *p-n*- junctions [7-9]. To increase sharpness of diffusive-junction and implanted-junction rectifiers are could be used inhomogenous distribution of temperature during laser and microwave annealing [10-14], radiation processing [15], native defects in materials (such as dislocations of discrepancy in heterostructures) [16]. In this paper based on recently introduce approach [17-23] we consider an alternative approach to increase sharpness of diffusive-junction and implanted-junction rectifiers. Framework the approach we consider heterostructure, which consist of a substrate and an epitaxial layer (see Fig. 1). The epitaxial layer consists of some materials. Some dopants

have been infused into the epitaxial layer by the way, which has been presented in the Fig. 1. Further we consider annealing of the dopants with optimal continuance [17-23] to achievement nearest interfaces of the heterostructure by the dopant. Main aim of the present paper is analysis of dynamics of redistribution of dopant in the heterostructure and estimation of the optimal annealing time.

Figure 1a. Heterostructure with two layers. View from one side

Figure 1b. Heterostructure with two layers. View from above

2. Method of Solution

Let us described redistribution of dopant during annealing in presented on Fig. 1 heterostructure by the second Fick's law in the following form [3,24]

$$\frac{\partial C(x, y, z, t)}{\partial t} = \frac{\partial}{\partial x} \left[D_C \frac{\partial C(x, y, z, t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_C \frac{\partial C(x, y, z, t)}{\partial y} \right] +$$

$$+ \frac{\partial}{\partial z} \left[D_c \frac{\partial C(x, y, z, t)}{\partial z} \right], \quad (1)$$

where $C(x, y, z, t)$ is the spatio-temporal distribution of dopant; D_c is the dopant diffusion coefficient. Value of the dopant diffusion coefficient depends on properties of materials of heterostructure, speed of heating and cooling of heterostructure. The dependences could be approximated by the following function [24]

$$D(x, y, z, t) = D_L(x, y, z, T) \left[1 + \xi \frac{C^\gamma(x, y, z, t)}{P^\gamma(x, y, z, T)} \right], \quad (2)$$

where $D_L(x, y, z, T)$ is the dopant diffusion coefficient for low level of doping; $P(x, y, z, T)$ is the limit of solubility of dopant; parameter γ depends on properties of materials of heterostructure and could be integer in the following interval $\gamma \in [1, 3]$ [24]. Spatio-temporal distribution of temperature, which leads to variation of dopant diffusion coefficient, we describe by the second law of Fourier [25]

$$\begin{aligned} c(T) \frac{\partial T(x, y, z, t)}{\partial t} = & \frac{\partial}{\partial x} \left[\lambda(x, y, z, T) \frac{\partial T(x, y, z, t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[\lambda(x, y, z, T) \frac{\partial T(x, y, z, t)}{\partial y} \right] + \\ & + \frac{\partial}{\partial z} \left[\lambda(x, y, z, T) \frac{\partial T(x, y, z, t)}{\partial z} \right] + p(x, y, z, t), \end{aligned} \quad (3)$$

where $c(T)$ is the heat capacitance of heterostructure. Temperature distribution of the capacitance could be approximated by the following relation: $c(T) = \text{cass}\{1 - \omega \cdot \exp[-\zeta \cdot T(x, y, z, t)/T_d]\}$ (see, for example, [25]). In the most interest interval of temperature, when current temperature $T(x, y, z, t)$ is larger, than Debye temperature T_d , one can consider the following limiting case $c(T) \approx \text{cass}$ [25]; $p(x, y, z, t)$ is the volumetric density of power, which the considered heterostructure absorbing during annealing of dopant; $\lambda(x, y, z, T)$ is the heat conduction coefficient. Temperature dependence of the heat conduction coefficient could be approximated by the following polynomial function: $\lambda(x, y, z, T) = \lambda_{\text{ass}}(x, y, z) [1 + \mu \cdot T_d \phi/T \phi(x, y, z, t)]$. Equations (1) and (3) should be complemented by the boundary and initial conditions

$$\begin{aligned} \frac{\partial C(0, y, z, t)}{\partial x} = 0, \quad \frac{\partial C(L_x, y, z, t)}{\partial x} = 0, \quad \frac{\partial C(x, 0, z, t)}{\partial y} = 0, \quad \frac{\partial C(x, L_y, z, t)}{\partial y} = 0, \\ \frac{\partial C(x, y, 0, t)}{\partial z} = 0, \quad \frac{\partial C(x, y, L_z, t)}{\partial z} = 0, \quad \frac{\partial T(0, y, z, t)}{\partial x} = 0, \quad \frac{\partial T(L_x, y, z, t)}{\partial x} = 0, \\ \frac{\partial T(x, 0, z, t)}{\partial y} = 0, \quad \frac{\partial T(x, L_y, z, t)}{\partial y} = 0, \quad \frac{\partial T(x, y, 0, t)}{\partial z} = 0, \quad \frac{\partial T(x, y, L_z, t)}{\partial z} = 0, \\ C(x, y, z, 0) = f_C(x, y, z), \quad T(x, y, z, 0) = T_r, \end{aligned} \quad (4)$$

where T_r is the equilibrium distribution of temperature, which coincides with it's equilibrium distribution.

First of all we estimate spatiotemporal distribution of temperature. In the common case exact solution of Eq. (3) is unknown. To obtain an approximate solution we transform the Eq. (3) to the following integro-differential form

$$\begin{aligned} T(x, y, z, t) = & T(x, y, z, t) + \frac{1}{T_d^3 \sqrt{L_x L_y L_z}} \left(\int_0^t \int_0^y \int_0^z [T^\phi(x, v, w, \tau) + \mu \cdot T_d^\phi] \frac{\partial T(x, v, w, \tau)}{\partial x} \times \right. \\ & \left. \alpha_{\text{ass}}(x, v, w) T(x, v, w, \tau) dv dw d\tau + \int_0^t \int_0^x \int_0^z \alpha_{\text{ass}}(u, y, w) T(u, y, w, \tau) [T^\phi(u, y, w, \tau) + \right. \end{aligned}$$

$$\begin{aligned}
& \mu \cdot T_d^\phi \left] \frac{\partial T(u, v, w, \tau)}{\partial y} d w d u d \tau + \int_0^t \int_0^x \int_0^y \alpha_{ass}(u, v, z) T(u, v, z, \tau) \left[T^\phi(u, v, z, \tau) + \mu \cdot T_d^\phi \right] \times \right. \\
& \frac{\partial T(u, v, z, \tau)}{\partial z} d v d u d \tau - \int_0^t \int_0^x \int_0^y \int_0^z \frac{\partial T(u, v, w, \tau)}{\partial u} \frac{\partial \left\{ T(u, v, w, \tau) \left[T^\phi(u, v, w, \tau) + \mu \cdot T_d^\phi \right] \right\}}{\partial u} \times \\
& \alpha_{ass}(u, v, w) d w d v d u d \tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \frac{\partial \left\{ T(u, v, w, \tau) \left[T^\phi(u, v, w, \tau) + \mu \cdot T_d^\phi \right] \right\}}{\partial v} \times \\
& \frac{\partial T(u, v, w, \tau)}{\partial v} d w d v d u d \tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \frac{\partial \left\{ T(u, v, w, \tau) \left[T^\phi(u, v, w, \tau) + \mu \cdot T_d^\phi \right] \right\}}{\partial w} \times \\
& \frac{\partial T(u, v, w, \tau)}{\partial w} d w d v d u d \tau - \mu \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\frac{\partial T(u, v, w, \tau)}{\partial u} \right]^2 d w d v d u d \tau \times (5) \\
& \phi \cdot T_d^\phi - \phi \cdot \mu \cdot T_d^\phi \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\frac{\partial T(u, v, w, \tau)}{\partial v} \right]^2 d w d v d u d \tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \times \\
& \phi \cdot \mu \cdot T_d^\phi \left[\frac{\partial T(u, v, w, \tau)}{\partial v} \right]^2 d w d v d u d \tau - \int_0^x \int_0^y \int_0^z \frac{T^{\phi+2}(u, v, w, t)}{\phi + 2} d w d v d u - \phi \cdot \mu \cdot T_d^\phi \times \\
& \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\frac{\partial T(u, v, w, \tau)}{\partial w} \right]^2 d w d v d u d \tau + \int_0^t \int_0^x \int_0^y \int_0^z T^{\phi+1}(u, v, w, \tau) \times \\
& \left. \frac{p(u, v, w, \tau)}{c_{ass}} d w d v d u d \tau + \int_0^x \int_0^y \int_0^z T^{\phi+1}(u, v, w, t) f_T(u, v, w) d w d v d u \right).
\end{aligned}$$

We solved the Eq.(5) by method of averaging of function corrections [26] with decreased quantity of iteration steps [27]. To decreased quantity of iteration steps with fixed value of exactness of solution we used exacter initial-order approximation of spatiotemporal distribution of temperature. We used solution of the Eq.(3) with averaged value of thermal diffusivity α_{0ass} as the exacter initial-order approximation of spatiotemporal distribution of temperature. The solution could be obtained by standard approaches [28,29] and could be approximated by the following sum

$$\tilde{T}(x, y, z, t) = T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(x) c_n(y) c_n(z) e_{nT}(t), \quad (6)$$

where $F_{nT}(t) = \int_0^t e_{nT}(-\tau) \int_0^{L_x} c_n(u) \int_0^{L_y} c_n(v) \int_0^{L_z} c_n(w) \frac{p(u, v, w, \tau)}{c_{ass}} d w d v d u d \tau$, $\text{cn}(s) = \cos(\pi n s / L_s)$, $s =$

x, y, z , $e_{nT}(t) = \exp \left[-\pi^2 n^2 \alpha_{ass} t \left(\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2} \right) \right]$. Substitution of the relation (6) into the right side of the

Eq.(5) instead of the function $T(x, y, z, t)$ gives us possibility to obtain the first-order approximation $T_1(x, y, z, t)$ framework the method of averaged of function correction with decreased quantity of iteration steps in the following form

$$T_1(x, y, z, t) = T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(x) c_n(y) c_n(z) e_{nT}(t) + \frac{1}{\sqrt[3]{L_x L_y L_z}} \left[- \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(x, v, w) \times \right.$$

$$\begin{aligned}
& \left[T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(x) c_n(u) c_n(v) e_{nT}(\tau) \right] \left\{ \left[T_r + \sum_{m=1}^{\infty} F_{mT}(t) c_m(x) c_m(u) c_m(v) e_{mT}(\tau) \times \right. \right. \\
& \left. \left. \frac{2}{L_x L_y L_z} \right]^\phi + \mu \cdot T_d^\phi \left\{ \frac{2\pi}{L_x^2 L_y L_z} \sum_{l=1}^{\infty} l \cdot F_{lT}(t) s_l(x) c_l(v) c_l(w) e_{lT}(\tau) d w d v d \tau - \int_0^t \int_0^x \int_0^z \left[T_r + \frac{2}{L_x L_y} \times \right. \right. \right. \\
& \left. \left. \frac{1}{L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(u) c_n(y) c_n(w) e_{nT}(\tau) \right] \alpha_{ass}(u, y, w) \left\{ \left[T_r + \sum_{m=1}^{\infty} F_{mT}(t) c_m(u) c_m(v) c_m(w) e_{mT}(\tau) \times \right. \right. \right. \\
& \left. \left. \frac{2}{L_x L_y L_z} \right]^\phi + \mu \cdot T_d^\phi \left\{ \frac{2\pi}{L_x L_y L_z} \sum_{l=1}^{\infty} l \cdot F_{lT}(t) c_l(u) s_l(v) c_l(w) e_{lT}(\tau) d w d u d \tau - \int_0^t \int_0^x \int_0^y \alpha_{ass}(u, v, z) \times \right. \right. \\
& \left. \left[T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(u) c_n(y) c_n(w) e_{nT}(\tau) \right] \left\{ \left[T_r + \frac{2}{L_x L_y L_z} \sum_{m=1}^{\infty} F_{mT}(t) c_m(u) c_m(v) c_m(w) \times \right. \right. \\
& \left. \left. e_{mT}(\tau) \right]^\phi + \mu \cdot T_d^\phi \left\{ \frac{2\pi}{L_x L_y L_z} \sum_{l=1}^{\infty} l \cdot F_{lT}(t) c_l(u) c_l(v) s_l(w) e_{lT}(\tau) d w d v d \tau + \frac{2\pi}{L_x^2 L_y L_z} \sum_{n=1}^{\infty} \int_0^t F_{nT}(\tau) \times \right. \right. \\
& \left. n \cdot e_{nT}(\tau) \int_0^x s_n(u) \int_0^y c_n(v) \int_0^z c_n(w) \alpha_{ass}(u, v, w) \frac{\partial}{\partial u} \left(\left[T_r + \sum_{m=1}^{\infty} F_{mT}(\tau) c_m(u) c_m(v) c_m(w) e_{mT}(\tau) \right] \frac{2}{L_x} \times \right. \right. \\
& \left. \left. \frac{1}{L_y L_z} \right) \right\} \left\{ \left[T_r + \frac{2}{L_x L_y L_z} \sum_{l=1}^{\infty} F_{lT}(\tau) c_l(u) c_l(v) c_l(w) e_{lT}(\tau) \right]^\phi + \mu \cdot T_d^\phi \right\} d w d v d u d \tau + \frac{2}{L_x} \times \\
& \frac{2\pi}{L_x L_y^2 L_z} \sum_{n=1}^{\infty} n \int_0^t F_{nT}(\tau) e_{nT}(\tau) \int_0^x c_n(u) \int_0^y s_n(v) \int_0^z c_n(w) \alpha_{ass}(u, v, w) \frac{\partial}{\partial v} \left(\left[T_r + \frac{2}{L_x L_y L_z} \sum_{l=1}^{\infty} F_{lT}(\tau) \times \right. \right. \\
& c_l(u) c_l(v) c_l(w) e_{lT}(\tau) \left. \right) \left\{ \left[T_r + \frac{2}{L_x L_y L_z} \sum_{m=1}^{\infty} F_{mT}(\tau) c_m(u) c_m(v) c_m(w) e_{mT}(\tau) \right]^\phi + \mu \cdot T_d^\phi \right\} \times \\
& d w d v d u d \tau + \frac{2\pi}{L_x L_y L_z} \sum_{n=1}^{\infty} n \int_0^t F_{nT}(\tau) e_{nT}(\tau) \int_0^x c_n(u) \int_0^y c_n(v) \int_0^z s_n(w) \alpha_{ass}(u, v, w) \frac{\partial}{\partial w} \left(\left[T_r + \right. \right. \\
& \left. \frac{2}{L_x L_y L_z} \sum_{l=1}^{\infty} F_{lT}(\tau) c_l(u) c_l(v) c_l(w) e_{lT}(\tau) \right) \left\{ \left[T_r + \frac{2}{L_x} \sum_{m=1}^{\infty} F_{mT}(\tau) c_m(u) c_m(v) c_m(w) e_{mT}(\tau) \times \right. \right. \\
& \left. \left. \frac{1}{L_y L_z} \right]^\phi + \mu \cdot T_d^\phi \right\} d w d v d u d \tau - 4\phi \frac{\mu \pi^2 T_d^\phi}{L_x^4 L_y^2 L_z} \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\sum_{n=1}^{\infty} F_{nT}(\tau) s_n(u) \times \right. \\
& \left. n^2 \cdot c_n(v) c_n(w) e_{nT}(\tau) \right]^2 d w d v d u d \tau - 4\phi \frac{\mu \pi^2 T_d^\phi}{L_x^2 L_y^4 L_z} \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\sum_{n=1}^{\infty} n^2 F_{nT}(\tau) c_n(u) \times \right.
\end{aligned}$$

$$\begin{aligned}
& s_n(v)c_n(w)e_{nT}(\tau)]^2 dwdvdud\tau - 4\phi \frac{\mu\pi^2 T_d^\phi}{L_x^2 L_y^2 L_z^2} \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \left[\sum_{n=1}^{\infty} F_{nT}(\tau) c_n(u)c_n(v) \times \right. \\
& \left. n^2 s_n(w)e_{nT}(\tau) \right]^2 dwdvdud\tau - \frac{1}{\phi+2} \int_0^t \int_0^x \int_0^y \int_0^z \left[\frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(u)c_n(v)c_n(w)e_{nT}(t) + \right. \\
& \left. T_r \right]^{\phi+2} dwdvdud\tau + \int_0^t \int_0^x \int_0^y \int_0^z \frac{p(u,v,w,\tau)}{c_{ass}} \left[T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(u)c_n(v)c_n(w)e_{nT}(\tau) \right]^{\phi+1} \times \\
& dwdvdud\tau + \int_0^t \int_0^x \int_0^y \int_0^z \left[T_r + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT}(t) c_n(u)c_n(v)c_n(w)e_{nT}(t) \right]^{\phi+1} f_T(u,v,w)dw \times \\
& dwdvdud\tau \Big] \frac{1}{T_d^\phi}, \tag{7}
\end{aligned}$$

where $\text{sn}(x) = \sin(\pi x/L)$. The second-order approximation of temperature $T_2(x,t)$ framework modified method of averaged of function correction could be determined by using standard procedure (see, for example, [26]). Framework the approach we replace the function $T(x,t)$ in the right side of Eq.(5) on the following sum: $T(x,y,z,t) \rightarrow \alpha_2 T + T_1(x,y,z,t)$. The replacement leads to the following result

$$\begin{aligned}
T_2(x,y,z,t) = & \alpha_{2T} + T_1(x,y,z,t) + \frac{1}{T_d^\phi \sqrt[3]{L_x L_y L_z}} \left[\int_0^t \int_0^x \int_0^y \int_0^z [\alpha_{2T} + T_1(x,v,w,\tau)] \{ [T_1(x,v,w,\tau) + \right. \\
& \left. \alpha_{2T}]^\phi + \mu \cdot T_d^\phi \} \alpha_{ass}(x,v,w) \frac{\partial T_1(x,v,w,\tau)}{\partial x} dwdvdud\tau + \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,y,w) \{ [T_1(u,y,w,\tau) + \right. \\
& \left. \alpha_{2T}]^\phi + \mu \cdot T_d^\phi \} [\alpha_{2T} + T_1(u,y,w,\tau)] \frac{\partial T_1(u,y,w,\tau)}{\partial y} dwdud\tau + \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,z) [\alpha_{2T} + \right. \\
& \left. T_1(u,v,z,\tau)] \{ [\alpha_{2T} + T_1(u,v,z,\tau)]^\phi + \mu \cdot T_d^\phi \} \frac{\partial T_1(u,v,z,\tau)}{\partial z} dwdud\tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \times \\
& \frac{\partial \left([\alpha_{2T} + T_1(u,v,w,\tau)] \{ [\alpha_{2T} + T_1(u,v,w,\tau)]^\phi + \mu \cdot T_d^\phi \} \right)}{\partial u} \frac{\partial T_1(u,v,w,\tau)}{\partial u} dwdvdud\tau - \\
& \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \frac{\partial T_1(u,v,w,\tau)}{\partial u} \frac{\partial}{\partial v} \left([\alpha_{2T} + T_1(u,v,w,\tau)] \{ [\alpha_{2T} + T_1(u,v,w,\tau)]^\phi + \mu \times \right. \\
& \left. T_d^\phi \} \right) dwdvdud\tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \frac{\partial T_1(u,v,w,\tau)}{\partial w} \frac{\partial}{\partial w} \left([\alpha_{2T} + T_1(u,v,w,\tau)] \{ \mu \cdot T_d^\phi + \right. \\
& \left. [\alpha_{2T} + T_1(u,v,w,\tau)]^\phi \} \right) dwdvdud\tau - \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \left[\frac{\partial T_1(u,v,w,\tau)}{\partial u} \right]^2 dwdvdud\tau \times \\
& \left. d\tau \cdot \phi \cdot \mu \cdot T_d^\phi - \phi \cdot \mu \cdot T_d^\phi \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u,v,w) \left[\frac{\partial T_1(u,v,w,\tau)}{\partial v} \right]^2 dwdvdud\tau - \phi \cdot \mu \times \right.
\end{aligned}$$

$$\begin{aligned}
& T_d^\phi \int_0^t \int_0^x \int_0^y \int_0^z \alpha_{ass}(u, v, w) \left[\frac{\partial T_1(u, v, w, \tau)}{\partial w} \right]^2 dw dv du d\tau - \int_0^x \int_0^y \int_0^z \frac{[\alpha_{2T} + T_1(u, v, w, t)]^{\phi+2}}{\phi+2} dw \times \\
& dv du + \int_0^t \int_0^x \int_0^y \int_0^z [\alpha_{2T} + T_1(u, v, w, \tau)]^{\phi+1} \frac{p(u, v, w, \tau)}{c_{ass}} dw dv du d\tau + \int_0^x \int_0^y \int_0^z f_T(u, v, w) \times \\
& [\alpha_{2T} + T_1(u, v, w, \tau)]^{\phi+1} dw dv du
\end{aligned} \quad (8)$$

We determine the parameter α_{2T} by the following relation [26]

$$\alpha_{i\rho} = \frac{M_{i\rho} - M_{i-1\rho}}{L_x L_y L_z \Theta} \quad (9)$$

where $M_{i\rho} = \int_0^{\Theta} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} \rho_i(x, y, z, t) dz dy dx dt$, $\rho = T, C$. Substitution of the relations (7) and (8) into the relation (9) gives us possibility to obtain the following equation for the parameter α_{2T}

$$\begin{aligned}
& \int_0^{\Theta} \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) [\alpha_{2T} + T_1(x, y, z, t)] \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\} \times \\
& \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx (\Theta - t) dt + \int_0^{\Theta} (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} [\alpha_{2T} + T_1(x, y, z, t)] (L_z - \\
& z) \alpha_{ass}(x, y, z) \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\} \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt + \int_0^{\Theta} (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) [\alpha_{2T} + T_1(x, y, z, t)] \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\} \times \\
& \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt - \int_0^{\Theta} (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \frac{\partial}{\partial x} ([T_1(x, y, z, t) + \\
& \alpha_{2T}] \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\}) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx dt - \int_0^{\Theta} (\Theta - \\
& t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \frac{\partial}{\partial y} ([\alpha_{2T} + T_1(x, y, z, t)] \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\}) (L_z - \\
& z) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt - \int_0^{\Theta} \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \times \\
& \frac{\partial T_1(x, y, z, t)}{\partial z} \frac{\partial}{\partial z} ([\alpha_{2T} + T_1(x, y, z, t)] \left\{ [\alpha_{2T} + T_1(x, y, z, t)]^\phi + \mu \cdot T_d^\phi \right\}) dz dy dx (\Theta -
\end{aligned}$$

$$\begin{aligned}
& t) dt - \phi \cdot T_d^\phi \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx \times \\
& \mu \cdot (\Theta - t) dt - \phi \cdot \mu \cdot \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 (L_z - \\
& T_d^\phi dz dy dx dt - \phi \cdot T_d^\phi \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 \times \\
& \mu \cdot \alpha_{ass}(x, y, z) dz dy dx dt - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \frac{[\alpha_{2T} + T_1(x, y, z, t)]^{\phi+2}}{\phi + 2} dz (L_y - \\
& y) dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} [\alpha_{2T} + T_1(x, y, z, t)]^{\phi+1} \frac{p(x, y, z, t)}{c_{ass}} (L_z - \\
& z) dz dy dx dt + \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) [\alpha_{2T} + T_1(x, y, z, t)]^{\phi+1} f_T(x, y, z) dz dy \times \\
& (L_x - x) dx dt = 0.
\end{aligned} \tag{10}$$

Farther we consider some examples of values of parameter α_{2T} for different vales of parameter ϕ :

For $\phi = 1$

$$\alpha_{2T} = \sqrt[3]{\sqrt{q^2 + p^3} - q} - \sqrt[3]{\sqrt{q^2 + p^3} + q} + \frac{a_2}{3a_1},$$

where

$$\begin{aligned}
a_3 &= L_x^2 L_y^2 L_z^2 \frac{\Theta}{24}; \\
a_2 &= \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx \times \\
& (\Theta - t) dt - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - \\
& x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \times \\
& \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \frac{p(x, y, z, t)}{c_{ass}} (L_z - \\
& z) dz dy dx dt + \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) f_T(x, y, z) dz dy dx dt; \\
a_1 &= \int_0^\Theta (\Theta - t) \times \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) [2T_1(x, y, z, t) + \mu \cdot T_d] \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx dt +
\end{aligned}$$

$$\begin{aligned}
& \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) [2T_1(x, y, z, t) + \mu \cdot T_d] \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx (\Theta - \\
& t) dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) [2T_1(x, y, z, t) + \mu \cdot T_d] \frac{\partial T_1(x, y, z, t)}{\partial z} dz (L_y - \\
& y) dy dx dt - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1^2(x, y, z, t) dz dy dx dt - 2 \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx dt - 2 \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - 2 \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt + 2 \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx dt + 2 \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - \\
& y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) f_T(x, y, z) dz dy dx dt ; \\
& a_0 = \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& (L_z - z) \frac{\partial T_1(x, y, z, t)}{\partial x} [T_1^2(x, y, z, t) + \mu \cdot T_d T_1(x, y, z, t)] dz dy dx dt - \frac{1}{3} \int_0^\Theta \int_0^{L_x} (L_x - x) \times \\
& \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1^3(x, y, z, t) dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) (L_z - \\
& z) [T_1^2(x, y, z, t) + \mu \cdot T_d T_1(x, y, z, t)] \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \times \\
& \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) [T_1^2(x, y, z, t) + \mu \cdot T_d T_1(x, y, z, t)] \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt - \\
& \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) [2T_1(x, y, z, t) + \mu \cdot T_d] \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 (L_z - \\
& z) dz dy dx dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} [2T_1(x, y, z, t) + \mu \cdot T_d] \alpha_{ass}(x, y, z) \times
\end{aligned}$$

$$\begin{aligned}
& (L_z - z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& (L_z - z) \left[2T_1(x, y, z, t) + \mu \cdot T_d \right] \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt - \mu \cdot T_d^\phi \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - \\
& x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx dt - \mu \cdot T_d^\phi \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - \mu \cdot T_d^\phi \int_0^\Theta (\Theta - \\
& t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt + \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1^2(x, y, z, t) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx dt + \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - \\
& y) \int_0^{L_z} (L_z - z) f_T(x, y, z) T_1^2(x, y, z, t) dz dy dx dt,
\end{aligned}$$

$$q = -\frac{a_2^3}{27a_3^3} - \frac{a_1a_2}{6a_3^2} - \frac{a_0}{2a_3},$$

$$p = -\frac{a_1}{3a_3} - a_2^2/9a_3^2.$$

For $\varphi=2$

$$\alpha_{2T} = \frac{A_3 - A_4 A}{4A_4} + \sqrt{\frac{1}{4} \left(A - \frac{A_3}{A_4} \right)^2 - 4 \left(y - \frac{A_3 y + A_0}{A_4 A} \right)},$$

where

$$A_4 = L_x^2 L_y^2 L_z^2 \frac{\Theta}{32},$$

$$\begin{aligned}
A_3 = & \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial x} dz (L_y - \\
& y) dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt + \\
& \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y -
\end{aligned}$$

$$\begin{aligned}
& y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) dz dy dx dt - \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) dz dy (L_x - \\
& x) dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx dt + \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) f_T(x, y, z) dz dy dx dt, \\
& A_2 = 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - \\
& z) \alpha_{ass}(x, y, z) T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx dt + 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \times \\
& \alpha_{ass}(x, y, z) T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial y} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& 3 T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial z} dz (L_y - y) dy dx dt + 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& (L_y - y) T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt - 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - \\
& z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx dt - 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \times \\
& \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& 3 (L_z - z) \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt - \frac{3}{2} \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1^2(x, y, z, t) dz dy \times \\
& (L_x - x) dx dt + 3 \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx \times \\
& (\Theta - t) dt + 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1(x, y, z, t) f_T(x, y, z) dz dy dx dt, \\
& A_1 = \int_0^\Theta \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) [3 T_1^2(x, y, z, t) + \mu \cdot T_d^2] \frac{\partial T_1(x, y, z, t)}{\partial x} dz dy dx \times \\
& (\Theta - t) dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) [3 T_1^2(x, y, z, t) + \mu \cdot T_d^2] \frac{\partial T_1(x, y, z, t)}{\partial y} (L_z -
\end{aligned}$$

$$\begin{aligned}
& z) dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) [3T_1^2(x, y, z, t) + \mu \cdot T_d^2] \times \\
& \frac{\partial T_1(x, y, z, t)}{\partial z} dz dy dx dt - 6 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) T_1(x, y, z, t) \times \\
& (L_z - z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx dt - 6 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& (L_z - z) T_1(x, y, z, t) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - 6 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \times \\
& \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) T_1(x, y, z, t) \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - \\
& y) \int_0^{L_z} (L_z - z) T_1^3(x, y, z, t) dz dy dx dt + 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} T_1^2(x, y, z, t) \times \\
& (L_z - z) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx dt + 3 \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} T_1^2(x, y, z, t) (L_z - \\
& z) f_T(x, y, z) dz dy dx dt,
\end{aligned}$$

$$\begin{aligned}
A_0 &= \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) T_1(x, y, z, t) (L_z - z) \times \\
& \frac{\partial T_1(x, y, z, t)}{\partial x} [T_1^2(x, y, z, t) + \mu \cdot T_d^2] dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) \times \\
& (L_z - z) T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial y} [T_1^2(x, y, z, t) + \mu \cdot T_d^2] dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - \\
& x) \int_0^{L_y} (L_y - y) \int_0^{L_z} \alpha_{ass}(x, y, z) T_1(x, y, z, t) \frac{\partial T_1(x, y, z, t)}{\partial z} [T_1^2(x, y, z, t) + \mu \cdot T_d^2] dz dy dx \times \\
& dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} \alpha_{ass}(x, y, z) [3T_1^2(x, y, z, t) + \mu \cdot T_d^2] \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 (L_z - \\
& z) dz (L_y - y) dy dx dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} [3T_1^2(x, y, z, t) + \mu \cdot T_d^2] (L_z - \\
& z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \times
\end{aligned}$$

$$\begin{aligned}
& \alpha_{ass}(x, y, z) \left[3T_1^2(x, y, z, t) + \mu \cdot T_d^2 \right] \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt - 2\mu \cdot T_d^2 \int_0^\Theta (\Theta - t) \times \\
& \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial x} \right]^2 dz dy dx dt - 2\mu \cdot T_d^2 \int_0^\Theta (\Theta - \\
& t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial y} \right]^2 dz dy dx dt - 2\mu \cdot T_d^2 \times \\
& \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) \alpha_{ass}(x, y, z) \left[\frac{\partial T_1(x, y, z, t)}{\partial z} \right]^2 dz dy dx dt - \\
& \frac{1}{4} \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) T_1^4(x, y, z, t) dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - \\
& y) \int_0^{L_z} (L_z - z) T_1^3(x, y, z, t) \frac{p(x, y, z, t)}{c_{ass}} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - \\
& z) T_1^3(x, y, z, t) f_T(x, y, z) dz dy dx dt,
\end{aligned}$$

$$\begin{aligned}
A &= \sqrt{8y + \frac{A_3^2}{A_4^2} + 4 \frac{A_2}{A_4}}, \\
y &= \sqrt[3]{\sqrt{\tilde{q}^2 + \tilde{p}^3} - \tilde{q}} + \\
&\quad - \sqrt[3]{\sqrt{\tilde{q}^2 + \tilde{p}^3} + \tilde{q}} + \frac{c}{6}, \\
\tilde{q} &= A_0 \frac{4A_2A_4 + A_3^2}{32A_4^3} + \frac{A_3^3}{216A_4^3} - \frac{A_1^2}{32A_4^2} - \frac{A_3}{24} \frac{A_1A_3 + 4A_0A_4}{A_4^3}, \\
\tilde{p} &= \frac{A_1A_3}{6A_4^2} + \frac{2A_0}{3A_4} - \frac{A_2^2}{36A_4^2}.
\end{aligned}$$

To make qualitative analysis and to obtain some quantitative results it is usually enough to use the second-order approximation framework the method of averaging of function corrections (see, for example, [26,27]). In this situation we used only the second-order approximations of temperature and concentration of dopant. Farther we transform the Eq.(1) into the integro-differential form

$$\begin{aligned}
C(x, y, z, t) &= C(x, y, z, t) + \frac{1}{L_x L_y L_z} \left(\int_0^t \int_0^y \int_0^z \left[1 + \xi \frac{C^\gamma(x, v, w, t)}{P^\gamma(x, v, w, T)} \right] \frac{\partial C(x, v, w, \tau)}{\partial x} \times \right. \\
&\quad \left. D_L(x, v, w, T) dw dv d\tau + \int_0^t \int_0^x \int_0^z D_L(u, y, w, T) \frac{\partial C(u, y, w, \tau)}{\partial y} \left[\frac{C^\gamma(u, y, w, t)}{P^\gamma(u, y, w, T)} \right] \times \right) \quad (11)
\end{aligned}$$

$$\xi + 1] d w d u d \tau + \int_0^t \int_0^x \int_0^y D_L(u, v, z, T) \left[1 + \xi \frac{C^\gamma(u, v, z, t)}{P^\gamma(u, v, z, T)} \right] \frac{\partial C(u, v, z, \tau)}{\partial z} d v d u d \tau +$$

$$\int_0^x \int_0^y \int_0^z f_C(u, v, w) d w d v d u - \int_0^x \int_0^y \int_0^z C(u, v, w, t) d w d v d u \Bigg).$$

To determine analytical solution of the Eq.(11) we used method of averaging of function corrections [26] with decreased quantity of iteration steps [27]. Framework the approach to determine the first-order approximation of dopant concentration we replace the function C (x,y,z,t) in the right side of the Eq.(11) on the solution of the Eq. (1) with averaged value of diffusion coefficient D_{0L}. The solution could be written as

$$\tilde{C}(x, y, z, t) = \frac{F_{0C}}{L_x L_y L_z} + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nC} c_n(x) c_n(y) c_n(z) e_{nC}(t), \quad (12)$$

where

$$e_{nC}(t) = \exp \left[-\pi^2 n^2 D_{0L} t \left(\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2} \right) \right],$$

$$F_{nC}(t) = \int_0^{L_x} c_n(u) \int_0^{L_y} c_n(v) \int_0^{L_z} f_C(u, v, w) \times c_n(w) d w d v d u d \tau.$$

Substitution of the function (12) into the right side of the Eq. (11) instead of the function C (x,y,z,t) gives us possibility to obtain the first-order approximation of the dopant concentration

$$C_1(x, y, z, t) = \frac{F_{0C}}{L_x L_y L_z} + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nC} c_n(x) c_n(y) c_n(z) e_{nC}(t) + \frac{1}{L_x L_y L_z} \left[- \int_0^t \int_0^x \int_0^y \left\{ 1 + \right. \right.$$

$$\left. \frac{\xi}{P^\gamma(x, v, w, T)} \frac{2\pi}{L_x^2 L_y L_z} \left[\frac{F_{0C}}{L_x L_y L_z} + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nC} c_n(x) c_n(v) c_n(w) e_{nC}(\tau) \right]^\gamma \right\} \sum_{m=1}^{\infty} s_m(x) \times$$

$$m \cdot c_m(v) c_m(w) D_L(x, v, w, T) F_{mC} e_{mC}(\tau) d w d v d \tau - \frac{2\pi}{L_x L_y L_z^2} \int_0^t \int_0^x \int_0^y D_L(u, y, w, T) \left\{ 1 + \right.$$

$$\left. \frac{\xi}{P^\gamma(u, y, w, T)} \left[\frac{F_{0C}}{L_x L_y L_z} + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nC} c_n(u) c_n(y) c_n(w) e_{nC}(\tau) \right]^\gamma \right\} \sum_{m=1}^{\infty} F_{mC} c_m(u) s_m(y) \times$$

$$m \cdot c_m(w) e_{mC}(\tau) d w d u d \tau - \frac{2\pi}{L_x L_y L_z^2} \int_0^t \int_0^x \int_0^y D_L(u, v, z, T) \left\{ 1 + \frac{\xi}{P^\gamma(u, v, z, T)} \left[\frac{F_{0C}}{L_x L_y L_z} + \right. \right.$$

$$\left. \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nC} c_n(u) c_n(v) c_n(z) e_{nC}(\tau) \right]^\gamma \right\} \sum_{m=1}^{\infty} m \cdot F_{mC} c_m(u) c_m(v) s_m(z) e_{mC}(\tau) d v d u \times$$

$$d \tau - \frac{F_{0C} x y z}{L_x L_y L_z} + \frac{2}{\pi^3} \sum_{n=1}^{\infty} F_{nC} s_n(x) s_n(y) s_n(z) e_{nC}(t) + \int_0^x \int_0^y \int_0^z f_C(u, v, w) d w d v d u \Bigg].$$

$$d\tau - \frac{F_{0C}xyz}{L_x L_y L_z} + \frac{2}{\pi^3} \sum_{n=1}^{\infty} F_{nC} s_n(x) s_n(y) s_n(z) e_{nC}(t) + \int_0^x \int_0^y \int_0^z f_C(u, v, w) dw dv du \Bigg]. \quad (13)$$

The second-order approximation of dopant concentration could be calculated by standard iteration procedure [26,27], i.e. by replacement of the function $C(x,y,z,t)$ in the right side of the Eq.(11) on the following sum: $C(x,y,z,t) \rightarrow \alpha_{2C} + C_1(x,y,z,t)$. The replacement gives us the following result

$$\begin{aligned} C_2(x, y, z, t) = & \alpha_{2C} + C_1(x, y, z, t) + \left(\int_0^t \int_0^y \int_0^z \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, v, w, \tau)]^\gamma}{P^\gamma(x, v, w, T)} \right\} \frac{\partial C_1(x, v, w, \tau)}{\partial x} \times \right. \\ & D_L(x, v, w, T) dw dv d\tau + \int_0^t \int_0^x \int_0^z D_L(u, y, w, T) \frac{\partial C_1(u, y, w, \tau)}{\partial y} \left\{ \frac{[\alpha_{2C} + C_1(u, y, w, \tau)]^\gamma}{P^\gamma(u, y, w, t)} \times \right. \\ & \left. \xi + 1 \right\} dw du d\tau + \int_0^t \int_0^x \int_0^y f_C(u, v, w) dw dv du + \int_0^t \int_0^x \int_0^y D_L(u, v, z, T) \left\{ \frac{[\alpha_{2C} + C_1(u, v, z, \tau)]^\gamma}{P^\gamma(u, v, z, T)} \times \right. \\ & \left. \left. \xi + 1 \right\} \frac{\partial C_1(u, v, z, \tau)}{\partial z} dv du d\tau - \int_0^x \int_0^y \int_0^z [\alpha_{2C} + C_1(u, v, w, t)] dw dv du \right) \frac{1}{L_x L_y L_z}. \quad (14) \end{aligned}$$

Parameter α_{2C} could be determined by using the relation (9) [26,27]. Substitution of the relation (14) into the relation (9) gives us possibility to obtain the equation for calculation of the parameter α_{2C} in the following form

$$\begin{aligned} & \int_0^\Theta (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} (L_z - z) D_L(x, y, z, T) \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^\gamma}{P^\gamma(x, y, z, T)} \right\} \frac{\partial C_1(x, y, z, t)}{\partial x} dz \times \\ & (L_y - y) dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} (L_z - z) \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^\gamma}{P^\gamma(x, y, z, T)} \right\} \times \\ & D_L(x, y, z, T) \frac{\partial C_1(x, y, z, t)}{\partial y} dz dy dx dt + \int_0^\Theta (\Theta - t) \int_0^{L_x} (L_x - x) \int_0^{L_y} \int_0^{L_z} D_L(x, y, z, T) \times \\ & \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^\gamma}{P^\gamma(x, y, z, T)} \right\} \frac{\partial C_1(x, y, z, t)}{\partial z} dz (L_y - y) dy dx dt + \Theta \int_0^{L_x} (L_x - x) \times \\ & \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) f_C(x, y, z) dz dy dx - \int_0^\Theta \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} [C_1(x, y, z, t) + \\ & \alpha_{2C}] (L_z - z) dz dy dx = 0. \end{aligned}$$

Farther we consider some examples of values of parameter α_{2C} for different vales of parameter γ .

For $\gamma = 1$

$$\alpha_{2C} = \frac{E_{x10000}^{1110} - E_{x10011}^{0111} - \xi \cdot E_{x11111}^{0111} - E_{y10011}^{1011} - \xi \cdot E_{y11111}^{0111} - E_{z10011}^{1011} - \xi \cdot E_{z11111}^{0111} - F_C}{\xi \cdot E_{x10111}^{0111} + \xi \cdot E_{y10111}^{0111} + \xi \cdot E_{z10111}^{0111} - L_x^2 L_y^2 L_z^2 \Theta / 8},$$

where

$$E_{Sijklm}^{n_1 n_2 n_3 n_4} = \int_0^\Theta (\Theta - t)^{n_4} \int_0^{L_x} (L_x - x)^{n_1} \int_0^{L_y} (L_y - y)^{n_2} \int_0^{L_z} \frac{C_i^j(x, y, z, t)}{P^k(x, y, z, T)} \frac{\partial^l C_1(x, y, z, t)}{\partial S^l} (L_z - z)^{n_3} D_L^m(x, y, z, T) dz dy dx dt,$$

$$F_C = \int_0^{L_x} (L_x - x) \int_0^{L_y} (L_y - y) \int_0^{L_z} (L_z - z) f_C(x, y, z) dz dy dx,$$

$$a = \xi \cdot (E_{x10211}^{0111} + E_{y10211}^{1011} + E_{z10211}^{1101}),$$

$$b = 2\xi E_{x11211}^{0111} + 2\xi E_{y11211}^{1011} + 2\xi E_{z11211}^{1101} - L_x^2 L_y^2 L_z^2 \frac{\Theta}{8},$$

$$c = \Theta \times F_C + E_{x10011}^{0111} + \xi E_{x12211}^{0111} + E_{y10011}^{1011} + \xi E_{y12211}^{1011} + E_{z10011}^{1101} + \xi E_{z12211}^{1101} - E_{x100000}^{1110}.$$

For $\gamma = 2$

$$\alpha_{2C} = -\frac{b}{2a} + \sqrt{b^2 - 4 \cdot a \cdot c}.$$

For $\gamma = 3$

$$\alpha_{2C} = \sqrt[3]{\sqrt{\hat{q}^2 + \hat{p}^3} - \hat{q}} - \sqrt[3]{\sqrt{\hat{q}^2 + \hat{p}^3} + \hat{q}} - \frac{B}{3A}$$

where

$$A = \xi (E_{x10311}^{0111} + E_{y10311}^{1011} + E_{z10311}^{1101}),$$

$$B = 3\xi (E_{x11311}^{0111} + E_{y11311}^{1011} + E_{z11311}^{1101}),$$

$$C = 3E_{x12311}^{0111} \times \xi + 3\xi \cdot E_{y12311}^{1011} + 3\xi \cdot E_{z12311}^{1101} - L_x^2 L_y^2 L_z^2 \frac{\Theta}{8},$$

$$D = \xi (E_{x13311}^{0111} + E_{y13311}^{1011} + E_{z13311}^{1101}) + E_{x10011}^{0111} + E_{y10011}^{1011} + E_{z10011}^{1101} + E_{x10000}^{1110} + \Theta F_C,$$

$$\hat{q} = \frac{B^3}{27A^3} - \frac{BC}{6A^2} + \frac{D}{2A},$$

$$\hat{p} = \frac{3AC - B^2}{6A^2}.$$

Analysis of spatio-temporal distributions of dopant concentration and temperature has been done analytically by using the second-order approximation framework the method of averaging of function corrections. The approximations of dopant concentration and temperature have been refined numerically.

3. Discussion

In this section based on relations, calculated in the previous section, we analyzed dynamics of temperature and redistribution of concentration of dopant in presented on the Fig. 1 heterostructure. The Fig. 2 shows typical distributions in the neighborhood of an interface between layers of heterostructure under the conditions, when source of dopant is situated in

the left layer and the dopant diffusion coefficient of the left layer is larger, than the dopant diffusion coefficient of the right layer. The Fig. 2 also shows, that interface between layers of heterostructure gives us possibility to increase sharpness of p - n -junction and at the same time to increase homogeneity of dopant distribution in doped area. Increasing of sharpness of p - n -junction gives us possibility to decrease switching time of the junction. Increasing of homogeneity of dopant distribution gives us possibility to decrease local overheating during switching of the devices or to decrease dimensions of p - n -junctions and transistors with fixed value of local overheating. Similar constructions of transistors have been described in [6,30]. However, in these references it has been considered manufacturing of transistors in homogenous materials. Manufacturing transistors in heterostructures by diffusion and implantation of ions of dopant gives us possibility to obtain more compact transistors. Another way to obtain field-effect and bipolar transistors is epitaxial growth [31,32]. However it is more easy to use diffusion and implantation of ions of dopant for local doping of materials for manufacturing elements of integrated circuits.

Figure 2. Distributions of dopant in heterostructure, which presented in Fig. 1. Curves 1-3 (solid lines) correspond to calculated results. Curves 4 and 5 (points) are experimental results from Refs. [30,33]. Increasing of number of curve corresponds to increasing of difference between values of dopant diffusion coefficient in layers of heterostructure

Figure 3. Spatial distributions of dopant in heterostructure. Curve 1 is the required idealized distribution of dopant. Curves 2-4 are the real distributions of dopant for different values of annealing time. Increasing of number of curves corresponds to increasing of value of annealing time

It should be noted, that after annealing with small continuance dopant did not achieved interface between layers of heterostructure and distribution of concentration of dopant is not enough homogenous (see Fig. 3). Increasing of annealing time leads to increasing of homogeneity of dopant distribution. At large values of annealing time one can obtain too homogenous dopant distribution (see Fig. 3). In this situation one shall to determine compromise annealing time. We determine the compromise annealing time framework recently introduced criterion [17-23]. Framework the criterion we approximate real distribution of dopant by step-wise function (see Fig. 3). Farther we minimized the following mean-squared error

$$U = \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} [C(x, y, z, \Theta) - \psi(x, y, z)] dz dy dx, \quad (15).$$

where $\psi(x,y,z)$ is the step-wise approximation function, which presented on Fig. 3 as curve 1. Dependences of optimal annealing time, which has been obtain by minimization by the mean-squared error (15), on several parameters are presented on Fig. 4

Figure 4. Dependences of dimensionless compromise annealing time on some parameters of heterostructure. Curve 1 is the dependence of annealing time on the relation a/L for $\xi = \gamma = 0$ and $D1=D2$. Curve 2 is the dependence of annealing time on the parameter $\epsilon = 1-D1/D2$ for $a/L=1/2$ and $\xi = \gamma = 0$. Curve 3 is the dependence of annealing time on the parameter ξ for $a/L=1/2$ and $\epsilon = \gamma = 0$. Curve 4 is the dependence of annealing time on the parameter γ for $a/L=1/2$ and $\epsilon = \xi = 0$

4. Conclusion

In the present paper we introduce an approach to manufacture more compact bipolar heterotransistors. This approach based on using of inhomogeneity of heterostructure and optimization of annealing time.

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