MODIFICATION OF DOPANT CONCENTRATION PROFILE IN A FIELD-EFFECT HETERO-TRANSISTOR FOR MODIFICATION ENERGY BAND DIAGRAM

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ABSTRACT

In this paper we consider an approach of manufacturing more compact field-effect heterotransistors. The approach based on manufacturing a heterostructure, which consist of a substrate and an epitaxial layer with specific configuration. After that several areas of the epitaxial layer have been doped by diffusion or ion implantation with optimized annealing of dopant and /or radiation defects. At the same time we introduce an approach of modification of energy band diagram by additional doping of channel of the transistors. We also consider an analytical approach to model and optimize technological process.

KEYWORDS

Modification of profile of dopant; decreasing of dimension of field-effect transistor; modification of energy band diagram

1. INTRODUCTION

Development of solid state electronic leads to increasing performance of the appropriate electronic devices [1-11]. At the same time one can find increasing integration rate of integrated circuits [1-3,5,7]. In this situation dimensions of elements of integrated circuits decreases. To increase performance of solid-state electronics devices are now elaborating new technological processes of manufacturing of solid state electronic devices. Another ways to increase the performance are optimization of existing technological processes and determination new materials with higher values of charge carriers mobilities. To decrease dimensions of elements of integrated circuits they are elaborating new and optimizing existing technological processes. Framework this paper we introduce an approach to decrease dimensions of field-effect heterotransistors. At the same time we introduce an approach of modification of energy band diagram for regulation of transport of charge carriers. The approach based on manufacturing a field-effect transistor in the heterostructure from Fig. 1. The heterostructure consists of a substrate and an epitaxial layer. They are have been considered four sections in the epitaxial layer. The sections have been doped by diffusion or ion implantation. Left and right sections will be considered in future as source and drain, respectively. Both average sections became as channel of transistor. Using one section instead two sections leads to simplification of structure of transistor. However using additional doped section framework the channel of the considered transistor gives us possibility to modify energy band diagram in the structure. After finishing of the considered doping annealing of dopant and/or radiation defects should be done. Several conditions for achievement of decreasing of dimensions of the field-effect transistor have been formulated.

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2. METHOD OF SOLUTION

To solve our aim we determine spatio-temporal distributions of concentrations of dopants. We calculate the required distributions by solving the second Fick's law in the following form [12,13]

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

Boundary and initial conditions for the equations are

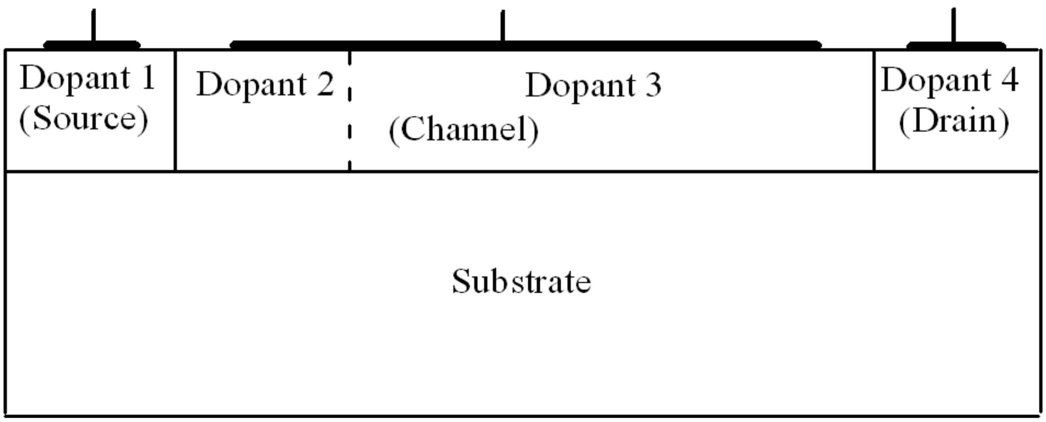

Fig. 1. Heterostructure, which consist of a substrate and an epitaxial layer.

View from side

$$\left.\frac{\partial C(x,y,z,t)}{\partial x}\right|_{x=0}=0,\ \left.\frac{\partial C(x,y,z,t)}{\partial x}\right|_{x=L_x}=0,\ \left.\frac{\partial C(x,y,z,t)}{\partial y}\right|_{y=0}=0,\ \left.\frac{\partial C(x,y,z,t)}{\partial y}\right|_{x=L_y}=0,$$

$$\left.\frac{\partial C(x,y,z,t)}{\partial z}\right|_{z=0}=0,\ \left.\frac{\partial C(x,y,z,t)}{\partial z}\right|_{x=L_z}=0,\ C(x,y,z,0)=f(x,y,z). \quad (2)$$

Here the function $C(x,y,z,t)$ describes the distribution of concentration of dopant in space and time. D_C describes distribution the dopant diffusion coefficient in space and as a function of temperature of annealing. Dopant diffusion coefficient will be changed with changing of materials of heterostructure, heating and cooling of heterostructure during annealing of dopant or radiation defects (with account Arrhenius law). Dependences of dopant diffusion coefficient on coordinate in heterostructure, temperature of annealing and concentrations of dopant and radiation defects could be written as [14-16]

$$D_C=D_L(x,y,z,T)\left[1+\xi\frac{C^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\right]\left[1+\varsigma_1\frac{V(x,y,z,t)}{V^*}+\varsigma_2\frac{V^2(x,y,z,t)}{(V^*)^2}\right]. \quad (3)$$

Here function $D_L(x,y,z,T)$ describes dependences of dopant diffusion coefficient on coordinate and temperature of annealing T. Function $P(x,y,z,T)$ describes the same dependences of the limit of solubility of dopant. The parameter γ is integer and usually could be varying in the following interval $\gamma\in[1,3]$. The parameter describes quantity of charged defects, which interacting (in average) with each atom of dopant. Ref.[14] describes more detailed information about dependence of dopant diffusion coefficient on concentration of dopant. Spatio-temporal distribution of concentration of radiation vacancies described by the function $V(x,y,z,t)$. The equilibrium distribution of concentration of vacancies has been denoted as V^*. It is known, that doping of materials by diffusion did not leads to radiation damage of materials. In this situation $\zeta_1=\zeta_2=0$. We determine spatio-temporal distributions of concentrations of radiation defects by solving the following system of equations [15,16]

$$\frac{\partial I(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_I(x,y,z,T)\frac{\partial I(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_I(x,y,z,T)\frac{\partial I(x,y,z,t)}{\partial y}\right]-k_{I,I}(x,y,z,T)\times$$
$$\times I^2(x,y,z,t)+\frac{\partial}{\partial z}\left[D_I(x,y,z,T)\frac{\partial I(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)\,I(x,y,z,t)\,V(x,y,z,t) \quad (4)$$

$$\frac{\partial V(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_V(x,y,z,T)\frac{\partial V(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_V(x,y,z,T)\frac{\partial V(x,y,z,t)}{\partial y}\right]-k_{V,V}(x,y,z,T)\times$$
$$\times V^2(x,y,z,t)+\frac{\partial}{\partial z}\left[D_V(x,y,z,T)\frac{\partial V(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)I(x,y,z,t)\,V(x,y,z,t).$$

Boundary and initial conditions for these equations are

$$\left.\frac{\partial \rho(x,y,z,t)}{\partial x}\right|_{x=0}=0,\ \left.\frac{\partial \rho(x,y,z,t)}{\partial x}\right|_{x=L_x}=0,\ \left.\frac{\partial \rho(x,y,z,t)}{\partial y}\right|_{y=0}=0,\ \left.\frac{\partial \rho(x,y,z,t)}{\partial y}\right|_{y=L_y}=0,$$
$$\left.\frac{\partial \rho(x,y,z,t)}{\partial z}\right|_{z=0}=0,\ \left.\frac{\partial \rho(x,y,z,t)}{\partial z}\right|_{z=L_z}=0,\ \rho(x,y,z,0)=f_\rho(x,y,z). \quad (5)$$

Here $\rho=I,V$. We denote spatio-temporal distribution of concentration of radiation interstitials as $I(x,y,z,t)$. Dependences of the diffusion coefficients of point radiation defects on coordinate and temperature have been denoted as $D_\rho(x,y,z,T)$. The quadric on concentrations terms of Eqs. (4) describes generation divacancies and diinterstitials. Parameter of recombination of point radiation defects and parameters of generation of simplest complexes of point radiation defects have been denoted as the following functions $k_{I,V}(x,y,z,T)$, $k_{I,I}(x,y,z,T)$ and $k_{V,V}(x,y,z,T)$, respectively.

Now let us calculate distributions of concentrations of divacancies $\Phi_V(x,y,z,t)$ and diinterstitials $\Phi_I(x,y,z,t)$ in space and time by solving the following system of equations [15,16]

$$\frac{\partial \Phi_I(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial y}\right]+$$
$$+\frac{\partial}{\partial z}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial z}\right]+k_{I,I}(x,y,z,T)I^2(x,y,z,t)-k_I(x,y,z,T)I(x,y,z,t) \quad (6)$$

$$\frac{\partial \Phi_V(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial y}\right]+$$
$$+\frac{\partial}{\partial z}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial z}\right]+k_{V,V}(x,y,z,T)V^2(x,y,z,t)-k_V(x,y,z,T)V(x,y,z,t).$$

Boundary and initial conditions for these equations are

$$\left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial x}\right|_{x=0}=0,\ \left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial x}\right|_{x=L_x}=0,\ \left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial y}\right|_{y=0}=0,\ \left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial y}\right|_{y=L_y}=0,$$

$$\left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial z}\right|_{z=0}=0,\ \left.\frac{\partial \Phi_\rho(x,y,z,t)}{\partial z}\right|_{z=L_z}=0,\ \Phi_I(x,y,z,0)=f_{\Phi I}(x,y,z),\ \Phi_V(x,y,z,0)=f_{\Phi V}(x,y,z).\quad (7)$$

The functions $D_{\Phi\rho}(x,y,z,T)$ describe dependences of the diffusion coefficients of the above complexes of radiation defects on coordinate and temperature. The functions $k_I(x,y,z,T)$ and $k_V(x,y,z,T)$ describe the parameters of decay of these complexes on coordinate and temperature.
To determine spatio-temporal distribution of concentration of dopant we transform the Eq.(1) to the following integro-differential form

$$\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}C(u,v,w,t)\,d\,w\,d\,v\,d\,u=\int\limits_0^t\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}D_L(x,v,w,T)\left[1+\varsigma_1\frac{V(x,v,w,\tau)}{V^*}+\varsigma_2\frac{V^2(x,v,w,\tau)}{(V^*)^2}\right]\times$$

$$\times\left[1+\xi\frac{C^\gamma(x,v,w,\tau)}{P^\gamma(x,v,w,T)}\right]\frac{\partial\,C(x,v,w,\tau)}{\partial\,x}\,d\,\tau\frac{y\,z}{L_yL_z}+\int\limits_0^t\int\limits_{L_x}^{x}\int\limits_{L_z}^{z}D_L(u,y,w,T)\left[1+\xi\frac{C^\gamma(u,y,w,\tau)}{P^\gamma(x,y,z,T)}\right]\times$$

$$\times\left[1+\varsigma_1\frac{V(u,y,w,\tau)}{V^*}+\varsigma_2\frac{V^2(u,y,w,\tau)}{(V^*)^2}\right]\frac{\partial\,C(u,y,w,\tau)}{\partial\,y}d\,\tau\frac{x\,z}{L_xL_z}+\int\limits_0^t\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}D_L(u,v,z,T)\times$$

$$\times\left[1+\varsigma_1\frac{V(u,v,z,\tau)}{V^*}+\varsigma_2\frac{V^2(u,v,z,\tau)}{(V^*)^2}\right]\left[1+\xi\frac{C^\gamma(u,v,z,\tau)}{P^\gamma(x,y,z,T)}\right]\frac{\partial\,C(u,v,z,\tau)}{\partial\,z}d\,\tau\frac{x\,y}{L_xL_y}+$$

$$+\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}f(u,v,w)\,d\,w\,d\,v\,d\,u\,.\quad (1a)$$

Now let us determine solution of Eq.(1*a*) by Bubnov-Galerkin approach [17]. To use the approach we consider solution of the Eq.(1*a*) as the following series

$$C_0(x,y,z,t)=\sum_{n=0}^{N}a_{nC}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{nC}(t).$$

Here $e_{nC}(t)=\exp\left[-\pi^2n^2D_{0C}t\left(L_x^{-2}+L_y^{-2}+L_z^{-2}\right)\right]$, $c_n(\chi)=cos(\pi n\chi/L_\chi)$. Number of terms N in the series is finite. The above series is almost the same with solution of linear Eq.(1) (i.e. for $\xi=0$) and averaged dopant diffusion coefficient D_0. Substitution of the series into Eq.(1*a*) leads to the following result

$$\frac{x\,y\,z}{\pi^2}\sum_{n=1}^{N}\frac{a_C}{n^3}s_n(x)\,s_n(y)\,s_n(z)\,e_{nC}(t)=-\frac{y\,z}{L_yL_z}\int\limits_0^t\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}\left\{1+\left[\sum_{n=1}^{N}a_{nC}\,c_n(x)\,c_n(v)\,c_n(w)\,e_{nC}(\tau)\right]^\gamma\times\right.$$

$$\left.\times\frac{\xi}{P^\gamma(x,v,w,T)}\right\}\left[1+\varsigma_1\frac{V(x,v,w,\tau)}{V^*}+\varsigma_2\frac{V^2(x,v,w,\tau)}{(V^*)^2}\right]D_L(x,v,w,T)\sum_{n=1}^{N}a_{nC}\,s_n(x)\,c_n(v)\times$$

$$\times n\,c_n(w)\,e_{nC}(\tau)d\,\tau-\frac{x\,z}{L_x L_z}\int\limits_0^t\int\limits_{L_x}^x\int\limits_{L_z}^z\left\{1+\left[\sum_{m=1}^N a_{mC}\,c_m(u)\,c_m(y)\,c_m(w)\,e_{mC}(\tau)\right]^\gamma\frac{\xi}{P^\gamma(u,y,w,T)}\right\}\times$$

$$\times D_L(u,y,w,T)\left[1+\varsigma_1\frac{V(u,y,w,\tau)}{V^*}+\varsigma_2\frac{V^2(u,y,w,\tau)}{(V^*)^2}\right]\sum_{n=1}^N n\,c_n(u)\,s_n(y)\,c_n(w)\,e_{nC}(\tau)\,d\,\tau\times$$

$$\times a_{nC}-\frac{x\,y}{L_x L_y}\int\limits_0^t\int\limits_{L_x}^x\int\limits_{L_y}^y D_L(u,v,z,T)\left\{1+\frac{\xi}{P^\gamma(u,v,z,T)}\left[\sum_{n=1}^N a_{nC}\,c_n(u)\,c_n(v)\,c_n(z)\,e_{nC}(\tau)\right]^\gamma\right\}\times$$

$$\times\left[1+\varsigma_1\frac{V(u,v,z,\tau)}{V^*}+\varsigma_2\frac{V^2(u,v,z,\tau)}{(V^*)^2}\right]\sum_{n=1}^N n\,a_{nC}c_n(u)\,c_n(v)\,s_n(z)\,e_{nC}(\tau)\,d\,\tau+\frac{x\,y\,z}{L_x L_y L_z}\times$$

$$\times\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z f(u,v,w)\,d\,w\,d\,v\,d\,u\,,$$

where $s_n(\chi)=sin(\pi n\,\chi/L_\chi)$. We used condition of orthogonality to determine coefficients a_n in the considered series. The coefficients a_n could be calculated for any quantity of terms N. In the common case the relations could be written as

$$-\frac{L_x^2L_y^2L_z^2}{\pi^5}\sum_{n=1}^N\frac{a_{nC}}{n^6}e_{nC}(t)=-\frac{L_y L_z}{2\pi^2}\int\limits_0^t\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}D_L(x,y,z,T)\left\{1+\left[\sum_{n=1}^N a_{nC}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{nC}(\tau)\right]^\gamma\times\right.$$

$$\left.\times\frac{\xi}{P^\gamma(x,y,z,T)}\right\}\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\sum_{n=1}^N\frac{a_{nC}}{n}s_n(2x)\,c_n(y)\,c_n(z)\,e_{nC}(\tau)\times$$

$$\times\left\{y\,s_n(y)+\frac{L_y}{\pi\,n}[c_n(y)-1]\right\}\left\{z\,s_n(z)+\frac{L_z}{\pi\,n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau-\int\limits_0^t\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}D_L(x,y,z,T)\times$$

$$\times D_L(x,y,z,T)\left\{1+\left[\sum_{n=1}^N a_{nC}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{nC}(\tau)\right]^\gamma\frac{\xi}{P^\gamma(x,y,z,T)}\right\}\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\right.$$

$$\left.+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\sum_{n=1}^N\left\{x\,s_n(x)+\frac{L_x}{\pi\,n}[c_n(x)-1]\right\}\frac{a_{nC}}{n}\times$$

$$\times\frac{L_x L_z}{2\pi^2}c_n(x)s_n(2y)\,c_n(z)\,e_{nC}(\tau)\left\{z\,s_n(z)+\frac{L_z}{\pi\,n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau-\frac{L_x L_y}{2\pi^2}\times$$

$$\times\int\limits_0^t\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}\left\{1+\left[\sum_{n=1}^N a_{nC}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{nC}(\tau)\right]^\gamma\frac{\xi}{P^\gamma(x,y,z,T)}\right\}\left[1+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}+\right.$$

$$\left.+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}\right]D_L(x,y,z,T)\sum_{n=1}^N\frac{a_{nC}}{n}c_n(x)\,c_n(y)\,s_n(z)\left\{x\,s_n(x)+\frac{L_x}{\pi\,n}[c_n(x)-1]\right\}\times$$

$$\times\left\{y\,s_n(y)+\frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}e_{nC}(\tau)\,d\,z\,d\,y\,d\,x\,d\,\tau+\sum_{n=1}^{N}\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{\pi n}\left[c_n(x)-1\right]\right\}\times$$

$$\times\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}\int_0^{L_z}\left\{z\,s_n(z)+\frac{L_z}{\pi n}\left[c_n(z)-1\right]\right\}f(x,y,z)\,d\,z\,d\,y\,d\,x\;.$$

As an example for $\gamma=0$ we obtain

$$a_{nC}=\int_0^{L_x}\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}\int_0^{L_z}\left\{z\,s_n(z)+\frac{L_y}{\pi n}\left[c_n(z)-1\right]\right\}f(x,y,z)\,d\,z\,d\,y\left\{x\,s_n(x)+\right.$$

$$\left.\times\left[c_n(x)-1\right]\frac{L_x}{\pi n}\right\}d\,x\left(\frac{n}{2}\left\{\int_0^{t}\int_0^{L_x}s_n(2x)\int_0^{L_y}c_n(y)\left\{y\,s_n(y)+\frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}\int_0^{L_z}D_L(x,y,z,T)\times\right.\right.$$

$$\times\left\{z\,s_n(z)+\frac{L_y}{\pi n}\left[c_n(z)-1\right]\right\}\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\left[1+\frac{\xi}{P^{\gamma}(x,y,z,T)}\right]\times$$

$$\times\,c_n(z)\,d\,z\,d\,y\,d\,x\,e_{nC}(\tau)\,d\,\tau+\int_0^{t}e_{nC}(\tau)\int_0^{L_x}c_n(x)\left\{x\,s_n(x)+\frac{L_y}{\pi n}\left[c_n(x)-1\right]\right\}\int_0^{L_y}s_n(2y)\int_0^{L_z}c_n(z)\times$$

$$\times\left\{z\,s_n(z)+\frac{L_y}{\pi n}\left[c_n(z)-1\right]\right\}\left[1+\frac{\xi}{P^{\gamma}(x,y,z,T)}\right]\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$$

$$\times\,D_L(x,y,z,T)\,d\,z\,d\,y\,d\,x\,d\,\tau+\int_0^{t}e_{nC}(\tau)\int_0^{L_x}c_n(x)\left\{x\,s_n(x)+\frac{L_x}{\pi n}\left[c_n(x)-1\right]\right\}\int_0^{L_y}c_n(y)\,\{\,s_n(y)\times$$

$$\times\,y+\frac{L_y}{\pi n}\left[c_n(y)-1\right]\Big\}\int_0^{L_z}s_n(2\,z)\,D_L(x,y,z,T)\left[1+\frac{\xi}{P^{\gamma}(x,y,z,T)}\right]\left[1+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}+\right.$$

$$\left.\left.\left.+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}\right]d\,z\,d\,y\,d\,x\,d\,\tau\right\}-\frac{L_z^2L_z^2L_z^2}{\pi^5n^6}e_{nC}(t)\right)^{-1}.$$

For $\gamma=1$ one can obtain the following relation to determine required parameters

$$a_{nC}=-\frac{\beta_n}{2\alpha_n}\pm\sqrt{\beta_n^2+4\alpha_n\int_0^{L_x}c_n(x)\int_0^{L_y}c_n(y)\int_0^{L_z}c_n(z)\,f(x,y,z)\,d\,z\,d\,y\,d\,x}\,,$$

where $\alpha_n=\dfrac{\xi\,L_yL_z}{2\pi^2n}\displaystyle\int_0^{t}e_{nC}(\tau)\int_0^{L_x}s_n(2x)\int_0^{L_y}c_n(y)\int_0^{L_z}c_n(z)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$

$$\times\frac{D_L(x,y,z,T)}{P(x,y,z,T)}\left\{y\,s_n(y)+\frac{L_y}{\pi n}[c_n(y)-1]\right\}\left\{z\,s_n(z)+\frac{L_z}{\pi n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau+\frac{\xi L_x L_z}{2\pi^2 n}\times$$

$$\times\int_0^t e_{nC}(\tau)\int_0^{L_x}c_n(x)\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\int_0^{L_z}c_n(z)\frac{D_L(x,y,z,T)}{P(x,y,z,T)}\left\{z\,s_n(z)-\frac{L_z}{\pi n}[c_n(z)-1]\right\}\times$$

$$\times\frac{D_L(x,y,z,T)}{P(x,y,z,T)}\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]d\,z\,s_n(2y)d\,y\,d\,x\,d\,\tau+\frac{\xi L_x L_y}{2\pi^2 n}\times$$

$$\times\int_0^t e_{nC}(\tau)\int_0^{L_x}c_n(x)\int_0^{L_y}c_n(y)\int_0^{L_z}s_n(2z)\frac{D_L(x,y,z,T)}{P(x,y,z,T)}\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$$

$$\times\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\left\{y\,s_n(y)+\frac{L_y}{\pi n}[c_n(y)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau,\ \beta_n=\frac{L_y L_z}{2n\pi^2}\int_0^t e_{nC}(\tau)\times$$

$$\times\int_0^{L_x}s_n(2x)\int_0^{L_y}c_n(y)\left\{y\,s_n(y)+\frac{L_y}{\pi n}[c_n(y)-1]\right\}\int_0^{L_z}c_n(z)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$$

$$\times D_L(x,y,z,T)\left\{z\,s_n(z)+\frac{L_z}{\pi n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau+\frac{L_x L_z}{2n\pi^2}\int_0^t e_{nC}(\tau)\int_0^{L_x}c_n(x)\int_0^{L_y}s_n(2y)\times$$

$$\times\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\int_0^{L_z}D_L(x,y,z,T)c_n(z)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$$

$$\times\left\{z\,s_n(z)+\frac{L_z}{\pi n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,d\,\tau+\frac{L_x L_y}{2n\pi^2}\int_0^t e_{nC}(\tau)\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\times$$

$$\times c_n(x)\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{\pi n}[c_n(y)-1]\right\}\int_0^{L_z}D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\times$$

$$\times s_n(2z)\,d\,z\,c_n(y)d\,y\,d\,x\,d\,\tau-L_x^2L_y^2L_z^2e_{nC}(t)/\pi^5n^6\ .$$

The same approach could be used for calculation parameters a_n for different values of parameter γ. However the relations are bulky and will not be presented in the paper. Advantage of the approach is absent of necessity to join dopant concentration on interfaces of heterostructure.

The same Bubnov-Galerkin approach has been used for solution the Eqs.(4). Previously we transform the differential equations to the following integro- differential form

$$\frac{x\,y\,z}{L_xL_yL_z}\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}I(u,v,w,t)\,d\,w\,d\,v\,d\,u=\frac{y\,z}{L_yL_z}\int_0^t\int_{L_y}^{y}\int_{L_z}^{z}D_I(x,v,w,T)\frac{\partial I(x,v,w,\tau)}{\partial x}d\,w\,d\,v\,d\,\tau+$$

$$+\frac{x\,z}{L_xL_z}\int_0^t\int_{L_x}^{x}\int_{L_z}^{z}D_I(u,y,w,T)\frac{\partial I(u,y,w,\tau)}{\partial x}d\,w\,d\,u\,d\,\tau-\frac{x\,y\,z}{L_xL_yL_z}\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}k_{I,V}(u,v,w,T)\,I(u,v,w,t)\times$$

$$\times V(u,v,w,t)\,d\,w\,d\,v\,d\,u+\frac{x\,y}{L_xL_y}\int\limits_0^t\int\limits_{L_x}^x\int\limits_{L_y}^y\frac{\partial I(u,v,z,\tau)}{\partial z}D_I(u,v,z,T)\,d\,v\,d\,u\,d\,\tau-\frac{x\,y\,z}{L_xL_yL_z}\times$$

$$\times\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z k_{I,I}(u,v,w,T)\,I^2(u,v,w,t)\,d\,w\,d\,v\,d\,u+\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z f_I(u,v,w)\,d\,w\,d\,v\,d\,u \qquad (4a)$$

$$\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z V(u,v,w,t)\,d\,w\,d\,v\,d\,u=\frac{y\,z}{L_yL_z}\int\limits_0^t\int\limits_{L_y}^y\int\limits_{L_z}^z D_V(x,v,w,T)\frac{\partial V(x,v,w,\tau)}{\partial x}d\,w\,d\,v\,d\,\tau+$$

$$+\frac{x\,z}{L_xL_z}\int\limits_0^t\int\limits_{L_x}^x\int\limits_{L_z}^z D_V(u,y,w,T)\frac{\partial V(u,y,w,\tau)}{\partial x}d\,w\,d\,u\,d\,\tau+\frac{x\,y}{L_xL_y}\int\limits_0^t\int\limits_{L_x}^x\int\limits_{L_y}^y\frac{\partial V(u,v,z,\tau)}{\partial z}\times$$

$$\times D_V(u,v,z,T)\,d\,v\,d\,u\,d\,\tau-\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z k_{I,V}(u,v,w,T)\,I(u,v,w,t)\,V(u,v,w,t)\,d\,w\,d\,v\,d\,u-$$

$$-\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z k_{V,V}(u,v,w,T)\,V^2(u,v,w,t)\,d\,w\,d\,v\,d\,u+\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z f_V(u,v,w)\,d\,w\,d\,v\,d\,u\,.$$

We determine spatio-temporal distributions of concentrations of point defects as the same series

$$\rho_0(x,y,z,t)=\sum_{n=1}^N a_{n\rho}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{n\rho}(t).$$

Parameters $a_{n\rho}$ should be determined in future. Substitution of the series into Eqs.(4a) leads to the following results

$$\frac{x\,y\,z}{\pi^3}\sum_{n=1}^N\frac{a_{nI}}{n^3}s_n(x)\,s_n(y)\,s_n(z)\,e_{nI}(t)=-\frac{y\,z\,\pi}{L_xL_yL_z}\sum_{n=1}^N a_{nI}\int\limits_0^t\int\limits_{L_y}^y c_n(y)\int\limits_{L_z}^z c_n(z)D_I(x,v,w,T)\,d\,w\,d\,v\times$$

$$\times e_{nI}(\tau)\,d\,\tau\,s_n(x)-\frac{x\,z\,\pi}{L_xL_yL_z}\sum_{n=1}^N a_{nI}\,s_n(y)\int\limits_0^t e_{nI}(\tau)\int\limits_{L_x}^x c_n(x)\int\limits_{L_z}^z c_n(z)D_I(u,y,w,T)\,d\,w\,d\,u\,d\,\tau-$$

$$-\frac{x\,y\,\pi}{L_xL_yL_z}\sum_{n=1}^N a_{nI}s_n(z)\int\limits_0^t e_{nI}(\tau)\int\limits_{L_x}^x c_n(x)\int\limits_{L_y}^y c_n(y)D_I(u,v,z,T)d\,v\,d\,u\,d\,\tau-\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z k_{I,I}(u,v,v,T)\times$$

$$\times\left[\sum_{n=1}^N a_{nI}\,c_n(u)\,c_n(v)\,c_n(w)\,e_{nI}(t)\right]^2 d\,w\,d\,v\,d\,u\frac{x\,y\,z}{L_xL_yL_z}-\frac{x\,y\,z}{L_xL_yL_z}\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z\sum_{n=1}^N a_{nI}\,c_n(u)\,c_n(v)\,c_n(w)\times$$

$$\times e_{nI}(t)\sum_{n=1}^N a_{nV}\,c_n(u)\,c_n(v)\,c_n(w)\,e_{nV}(t)k_{I,V}(u,v,v,T)\,d\,w\,d\,v\,d\,u+\int\limits_{L_x}^x\int\limits_{L_y}^y\int\limits_{L_z}^z f_I(u,v,w)\,d\,w\,d\,v\,d\,u\times$$

$$\times x\,y\,z/L_xL_yL_z$$

$$\frac{x\,y\,z}{\pi^3}\sum_{n=1}^N\frac{a_{nV}}{n^3}s_n(x)\,s_n(y)\,s_n(z)\,e_{nV}(t)=-\frac{y\,z\,\pi}{L_xL_yL_z}\sum_{n=1}^N a_{nV}\int\limits_0^t\int\limits_{L_y}^y c_n(y)\int\limits_{L_z}^z c_n(z)D_V(x,v,w,T)\,d\,w\,d\,v\times$$

$$\times e_{nV}(\tau)\,d\tau\, s_n(x) - \frac{x\,z\,\pi}{L_x L_y L_z}\sum_{n=1}^{N} a_{nV}\, s_n(y)\int_0^t e_{nV}(\tau)\int_{L_x}^{x} c_n(x)\int_{L_z}^{z} c_n(z) D_V(u,y,w,T)\,d\,w\,d\,u\,d\,\tau -$$

$$-\frac{x\,y\,\pi}{L_x L_y L_z}\sum_{n=1}^{N} a_{nV} s_n(z)\int_0^t e_{nV}(\tau)\int_{L_x}^{x} c_n(x)\int_{L_y}^{y} c_n(y) D_V(u,v,z,T)\,d\,v\,d\,u\,d\,\tau - \int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z} k_{V,V}(u,v,v,T)\times$$

$$\times\left[\sum_{n=1}^{N} a_{nV}\, c_n(u)\, c_n(v)\, c_n(w)\, e_{nI}(t)\right]^2 d\,w\,d\,v\,d\,u\frac{x\,y\,z}{L_x L_y L_z} - \frac{x\,y\,z}{L_x L_y L_z}\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}\sum_{n=1}^{N} a_{nI} c_n(u)\, c_n(v)\, c_n(w)\times$$

$$\times e_{nI}(t)\sum_{n=1}^{N} a_{nV}\, c_n(u)\, c_n(v)\, c_n(w)\, e_{nV}(t) k_{I,V}(u,v,v,T)\,d\,w\,d\,v\,d\,u + \int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z} f_V(u,v,w)\,d\,w\,d\,v\,d\,u\times$$

$$\times\, x\,y\,z/L_x L_y L_z\,.$$

We used orthogonality condition of functions of the considered series framework the heterostructure to calculate coefficients $a_{n\rho}$. The coefficients a_n could be calculated for any quantity of terms N. In the common case equations for the required coefficients could be written as

$$-\frac{L_x^2 L_y^2 L_z^2}{\pi^5}\sum_{n=1}^{N}\frac{a_{nI}}{n^6} e_{nI}(t) = -\frac{1}{2\pi L_x}\sum_{n=1}^{N}\frac{a_{nI}}{n^2}\int_0^t\int_0^{L_x}[1-c_n(2x)]\int_0^{L_y}\left\{L_y + y\, s_n(2y) + \frac{L_y}{2\pi n}[c_n(2y)-1]\right\}\times$$

$$\times\int_0^{L_z} D_I(x,y,z,T)\left\{z\, s_n(z) + \frac{L_z}{2\pi n}[c_n(z)-1]\right\} d\,z\,d\,y\,d\,x\, e_{nI}(\tau)\,d\,\tau - \frac{1}{2\pi L_y}\sum_{n=1}^{N}\frac{a_{nI}}{n^2}\int_0^t\int_0^{L_x}\{x\, s_n(2x) +$$

$$+L_x + \frac{L_x}{\pi n}[c_n(2x)-1]\Big\}\int_0^{L_y}\int_0^{L_z} D_I(x,y,z,T)\left\{L_z + z\, s_n(2z) + \frac{L_z}{2\pi n}[c_n(2z)-1]\right\} d\,z[1-c_n(2y)]\times$$

$$\times\, d\,y\,d\,x\, e_{nI}(\tau)\,d\,\tau\int_0^{L_z} D_I(x,y,z,T)\left\{L_z + z\, s_n(2z) + \frac{L_z}{2\pi n}[c_n(2z)-1]\right\} d\,z\,d\,y\,d\,x\, e_{nI}(\tau)\,d\,\tau -$$

$$-\frac{1}{2\pi L_z}\sum_{n=1}^{N}\frac{a_{nI}}{n^2}\int_0^t\int_0^{L_x}\left\{L_x + x\, s_n(2x) + \frac{L_x}{2\pi n}[c_n(2x)-1]\right\}\int_0^{L_y}\left\{L_y + y\, s_n(2y) + \frac{L_y}{2\pi n}[c_n(2y)-1]\right\}\times$$

$$\times\int_0^{L_z}[1-c_n(2z)] D_I(x,y,z,T)\,d\,z\,d\,y\,d\,x\, e_{nI}(\tau)\,d\,\tau - \sum_{n=1}^{N} a_{nI}^2 e_{nI}(2t)\int_0^{L_x}\left\{L_x + \frac{L_x}{2\pi n}[c_n(2x)-1] +\right.$$

$$\left.+\, x\, s_n(2x)\right\}\int_0^{L_y}\left\{L_y + y\, s_n(2y) + \frac{L_y}{2\pi n}[c_n(2y)-1]\right\}\int_0^{L_z} k_{I,I}(x,y,z,T)\left\{L_z + \frac{L_z}{2\pi n}[c_n(2z)-1] +\right.$$

$$\left.+\, z\, s_n(2z)\right\} d\,z\,d\,y\,d\,x - \sum_{n=1}^{N} a_{nI} a_{nV} e_{nI}(t) e_{nV}(t)\int_0^{L_x}\left\{L_x + x\, s_n(2x) + \frac{L_x}{2\pi n}[c_n(2x)-1]\right\}\int_0^{L_y}\{L_y +$$

$$+ y s_n(2y) + \frac{L_y}{2\pi n}\left[c_n(2y)-1\right]\Bigg\}\int_0^{L_z} k_{I,V}(x,y,z,T)\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\times$$

$$\times d\,y\,d\,x + \sum_{n=1}^{N}\int_0^{L_x}\left\{x s_n(x) + \frac{L_x}{\pi n}\left[c_n(x)-1\right]\right\}\int_0^{L_y}\left\{y s_n(y) + \frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}\int_0^{L_z} f_I(x,y,z,T)\times$$

$$\times\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\,d\,y\,d\,x$$

$$-\frac{L_x^2 L_y^2 L_z^2}{\pi^5}\sum_{n=1}^{N}\frac{a_{nV}}{n^6} e_{nV}(t) = -\frac{1}{2\pi L_x}\sum_{n=1}^{N}\frac{a_{nV}}{n^2}\int_0^t\int_0^{L_x}\left[1-c_n(2x)\right]\int_0^{L_y}\left\{L_y + y s_n(2y) + \frac{L_y}{2\pi n}\left[c_n(2y)-1\right]\right\}\times$$

$$\times\int_0^{L_z} D_V(x,y,z,T)\left\{z s_n(z) + \frac{L_z}{2\pi n}\left[c_n(z)-1\right]\right\} d\,z\,d\,y\,d\,x\,e_{nV}(\tau)\,d\,\tau - \frac{1}{2\pi L_y}\sum_{n=1}^{N}\frac{a_{nV}}{n^2}\int_0^t\int_0^{L_x}\{x s_n(2x) +$$

$$+ L_x + \frac{L_x}{\pi n}\left[c_n(2x)-1\right]\Bigg\}\int_0^{L_y}\int_0^{L_z} D_V(x,y,z,T)\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\left[1-c_n(2y)\right]\times$$

$$\times d\,y\,d\,x\,e_{nV}(\tau)\,d\,\tau\int_0^{L_z} D_V(x,y,z,T)\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\,d\,y\,d\,x\,e_{nV}(\tau)\,d\,\tau -$$

$$-\frac{1}{2\pi L_z}\sum_{n=1}^{N}\frac{a_{nV}}{n^2}\int_0^t\int_0^{L_x}\left\{L_x + x s_n(2x) + \frac{L_x}{2\pi n}\left[c_n(2x)-1\right]\right\}\int_0^{L_y}\left\{L_y + y s_n(2y) + \frac{L_y}{2\pi n}\left[c_n(2y)-1\right]\right\}\times$$

$$\times\int_0^{L_z}\left[1-c_n(2z)\right] D_V(x,y,z,T)\,d\,z\,d\,y\,d\,x\,e_{nV}(\tau)\,d\,\tau - \sum_{n=1}^{N} a_{nV}^2 e_{nV}(2t)\int_0^{L_x}\Bigg\{L_x + \frac{L_x}{2\pi n}\left[c_n(2x)-1\right] +$$

$$+ x s_n(2x)\Bigg\}\int_0^{L_y}\left\{L_y + y s_n(2y) + \frac{L_y}{2\pi n}\left[c_n(2y)-1\right]\right\}\int_0^{L_z} k_{V,V}(x,y,z,T)\Bigg\{L_z + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right] +$$

$$+ z s_n(2z)\Bigg\} d\,z\,d\,y\,d\,x - \sum_{n=1}^{N} a_{nI} a_{nV} e_{nI}(t) e_{nV}(t)\int_0^{L_x}\left\{L_x + x s_n(2x) + \frac{L_x}{2\pi n}\left[c_n(2x)-1\right]\right\}\int_0^{L_y}\Bigg\{L_y +$$

$$+ y s_n(2y) + \frac{L_y}{2\pi n}\left[c_n(2y)-1\right]\Bigg\}\int_0^{L_z} k_{I,V}(x,y,z,T)\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\times$$

$$\times d\,y\,d\,x + \sum_{n=1}^{N}\int_0^{L_x}\left\{x s_n(x) + \frac{L_x}{\pi n}\left[c_n(x)-1\right]\right\}\int_0^{L_y}\left\{y s_n(y) + \frac{L_y}{\pi n}\left[c_n(y)-1\right]\right\}\int_0^{L_z} f_V(x,y,z,T)\times$$

$$\times\left\{L_z + z s_n(2z) + \frac{L_z}{2\pi n}\left[c_n(2z)-1\right]\right\} d\,z\,d\,y\,d\,x\,.$$

In the final form relations for required parameters could be written as

$$a_{nI}=-\frac{b_3+A}{4b_4}\pm\sqrt{\frac{(b_3+A)^2}{4}-4b_4\left(y+\frac{b_3 y-\gamma_{nV}\lambda_{nI}^2}{A}\right)},\; a_{nV}=-\frac{\gamma_{nI}a_{nI}^2+\delta_{nI}a_{nI}+\lambda_{nI}}{\chi_{nI}a_{nI}},$$

where $\gamma_{n\rho}=e_{n\rho}(2t)\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}k_{\rho,\rho}(x,y,z,T)\left\{L_x+x\,s_n(2x)+\frac{L_x}{2\pi n}[c_n(2x)-1]\right\}\{y\,s_n(2y)+L_y+$

$+\frac{L_y}{2\pi n}[c_n(2y)-1]\Big\}\left\{L_z+z\,s_n(2z)+\frac{L_z}{2\pi n}[c_n(2z)-1]\right\}d\,z\,d\,y\,d\,x$, $\delta_{n\rho}=\frac{1}{2\pi L_x n^2}\int_0^t e_{n\rho}(\tau)\times$

$\times\int_0^{L_x}\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}\left\{z\,s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}D_\rho(x,y,z,T)\,d\,z\,d\,y\,[1-$

$-c_n(2x)]\,d\,x\,d\,\tau+\frac{1}{2\pi L_y n^2}\int_0^t e_{n\rho}(\tau)\int_0^{L_x}\left\{L_x+x\,s_n(2x)+\frac{L_x}{\pi n}[c_n(2x)-1]\right\}\int_0^{L_y}[1-c_n(2y)]\int_0^{L_z}\{L_z+$

$+z\,s_n(2z)+\frac{L_z}{2\pi n}[c_n(2z)-1]\Big\}D_\rho(x,y,z,T)d\,z\,d\,y\,d\,x\,d\,\tau+\frac{1}{2\pi L_z n^2}\int_0^t e_{n\rho}(\tau)\int_0^{L_x}\{x\,s_n(2x)+$

$+L_x+\frac{L_x}{\pi n}[c_n(2x)-1]\Big\}\int_0^{L_y}\left\{L_y+y\,s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}[1-c_n(2z)]D_\rho(x,y,z,T)\,d\,z\times$

$\times d\,y\,d\,x\,d\,\tau-\frac{L_x^2L_y^2L_z^2}{\pi^5 n^6}e_{n\rho}(t)$, $\chi_{nIV}=\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\Big\{L_y+\frac{L_y}{2\pi n}[c_n(2y)-1]+$

$+y\,s_n(2y)\Big\}\int_0^{L_z}k_{I,V}(x,y,z,T)\left\{L_z+z\,s_n(2z)+\frac{L_z}{2\pi n}[c_n(2z)-1]\right\}d\,z\,d\,y\,d\,x\,e_{nI}(t)\,e_{nV}(t)$,

$\lambda_{n\rho}=\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{\pi n}[c_n(y)-1]\right\}\int_0^{L_z}\left\{z\,s_n(z)+\frac{L_z}{\pi n}[c_n(z)-1]\right\}\times$
$\times f_\rho(x,y,z,T)d\,z\,d\,y\,d\,x$, $b_4=\gamma_{nV}\gamma_{nI}^2-\gamma_{nI}\chi_{nI}^2$, $b_3=2\gamma_{nV}\gamma_{nI}\delta_{nI}-\delta_{nI}\chi_{nI}^2-\delta_{nV}\chi_{nI}\gamma_{nI}$,
$A=\sqrt{8y+b_3^2-4b_2}$, $b_2=\gamma_{nV}\delta_{nI}^2+2\lambda_{nI}\gamma_{nV}\gamma_{nI}-\delta_{nV}\chi_{nI}\delta_{nI}+(\lambda_{nV}-\lambda_{nI})\chi_{nI}^2$, $b_1=2\lambda_{nI}\times$
$\times\gamma_{nV}\delta_{nI}-\delta_{nV}\chi_{nI}\lambda_{nI}$, $y=\sqrt[3]{\sqrt{q^2+p^3}-q}-\sqrt[3]{\sqrt{q^2+p^3}+q}-\frac{b_3}{3b_4}$, $p=\frac{3b_2b_4-b_3^2}{9b_4^2}$,
$q=\left(2b_3^3-9b_2b_3+27b_1b_4^2\right)/54b_4^3$.

We determine distributions of concentrations of simplest complexes of radiation defects in space and time as the following functional series

$$\Phi_{\rho 0}(x,y,z,t)=\sum_{n=1}^{N}a_{n\Phi\rho}\,c_n(x)\,c_n(y)\,c_n(z)\,e_{n\rho}(t).$$

Here $a_{n\Phi\rho}$ are the coefficients, which should be determined. Let us previously transform the Eqs. (6) to the following integro-differential form

$$\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}\Phi_I(u,v,w,t)\,d\,w\,d\,v\,d\,u=\int\limits_{0}^{t}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}D_{\Phi I}(x,v,w,T)\frac{\partial\,\Phi_I(x,v,w,\tau)}{\partial x}d\,w\,d\,v\,d\,\tau\times$$

$$\times\frac{y\,z}{L_y L_z}+\frac{x\,z}{L_x L_z}\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_z}^{z}D_{\Phi I}(u,y,w,T)\frac{\partial\,\Phi_I(u,y,w,\tau)}{\partial y}d\,w\,d\,u\,d\,\tau+\frac{x\,y}{L_x L_y}\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}D_{\Phi I}(u,v,z,T)\times$$

$$\times\frac{\partial\,\Phi_I(u,v,z,\tau)}{\partial z}d\,v\,d\,u\,d\,\tau+\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_{I,I}(u,v,w,T)\,I^2(u,v,w,\tau)\,d\,w\,d\,v\,d\,u- \quad (6a)$$

$$-\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_I(u,v,w,T)\,I(u,v,w,\tau)\,d\,w\,d\,v\,d\,u+\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}f_{\Phi I}(u,v,w)\,d\,w\,d\,v\,d\,u$$

$$\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}\Phi_V(u,v,w,t)\,d\,w\,d\,v\,d\,u=\int\limits_{0}^{t}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}D_{\Phi V}(x,v,w,T)\frac{\partial\,\Phi_V(x,v,w,\tau)}{\partial x}d\,w\,d\,v\,d\,\tau\times$$

$$\times\frac{y\,z}{L_y L_z}+\frac{x\,z}{L_x L_z}\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_z}^{z}D_{\Phi V}(u,y,w,T)\frac{\partial\,\Phi_V(u,y,w,\tau)}{\partial y}d\,w\,d\,u\,d\,\tau+\frac{x\,y}{L_x L_y}\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}D_{\Phi V}(u,v,z,T)\times$$

$$\times\frac{\partial\,\Phi_V(u,v,z,\tau)}{\partial z}d\,v\,d\,u\,d\,\tau+\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_{V,V}(u,v,w,T)\,V^2(u,v,w,\tau)\,d\,w\,d\,v\,d\,u-$$

$$-\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_V(u,v,w,T)\,V(u,v,w,\tau)\,d\,w\,d\,v\,d\,u+\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}f_{\Phi V}(u,v,w)\,d\,w\,d\,v\,d\,u\,.$$

Substitution of the previously considered series in the Eqs.(6*a*) leads to the following form

$$-x\,y\,z\sum_{n=1}^{N}\frac{a_{n\Phi I}}{\pi^3 n^3}s_n(x)\,s_n(y)\,s_n(z)\,e_{nI}(t)=-\frac{y\,z\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}n\,a_{n\Phi I}\,s_n(x)e_{nI}(t)\int\limits_{0}^{t}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}c_n(v)c_n(w)\times$$

$$\times D_{\Phi I}(x,v,w,T)\,d\,w\,d\,v\,d\,\tau-\frac{x\,z\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}a_{n\Phi I}\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_z}^{z}c_n(u)c_n(w)\,D_{\Phi I}(u,v,w,T)\,d\,w\,d\,u\,d\,\tau\times$$

$$\times n\,s_n(y)e_{n\Phi I}(t)-\frac{x\,y\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}n\,a_{n\Phi I}\,s_n(z)e_{n\Phi I}(t)\int\limits_{0}^{t}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}c_n(u)c_n(v)\,D_{\Phi I}(u,v,z,T)\,d\,v\,d\,u\,d\,\tau+$$

$$+\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_{I,I}(u,v,w,T)\,I^2(u,v,w,\tau)\,d\,w\,d\,v\,d\,u+\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}f_{\Phi I}(u,v,w)\,d\,w\,d\,v\,d\,u\times$$

$$\times\frac{x\,y\,z}{L_x L_y L_z}-\frac{x\,y\,z}{L_x L_y L_z}\int\limits_{L_x}^{x}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}k_I(u,v,w,T)\,I(u,v,w,\tau)\,d\,w\,d\,v\,d\,u$$

$$-x\,y\,z\sum_{n=1}^{N}\frac{a_{n\Phi V}}{\pi^3 n^3}s_n(x)\,s_n(y)\,s_n(z)\,e_{nV}(t)=-\frac{y\,z\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}n\,a_{n\Phi V}\,s_n(x)e_{nV}(t)\int\limits_{0}^{t}\int\limits_{L_y}^{y}\int\limits_{L_z}^{z}c_n(v)c_n(w)\times$$

$$\times D_{\Phi V}(x,v,w,T)\,d\,w\,d\,v\,d\,\tau-\frac{x\,z\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}n\int_0^t\int_{L_x}^{x}\int_{L_z}^{z}c_n(u)c_n(w)\,D_{\Phi V}(u,v,w,T)\,d\,w\,d\,u\,d\,\tau\times$$

$$\times a_{n\Phi V}\,s_n(y)e_{n\Phi V}(t)-\frac{x\,y\,\pi}{L_x L_y L_z}\sum_{n=1}^{N}n\,s_n(z)e_{n\Phi V}(t)\int_0^t\int_{L_x}^{x}\int_{L_y}^{y}c_n(u)c_n(v)\,D_{\Phi V}(u,v,z,T)\,d\,v\,d\,u\,d\,\tau\times$$

$$\times a_{n\Phi V}+\frac{x\,y\,z}{L_x L_y L_z}\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}k_{V,V}(u,v,w,T)V^2(u,v,w,\tau)d\,w\,d\,v\,d\,u+\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}f_{\Phi V}(u,v,w)d\,w\,d\,v\,d\,u\times$$

$$\times\frac{x\,y\,z}{L_x L_y L_z}-\frac{x\,y\,z}{L_x L_y L_z}\int_{L_x}^{x}\int_{L_y}^{y}\int_{L_z}^{z}k_V(u,v,w,T)\,V(u,v,w,\tau)d\,w\,d\,v\,d\,u\,.$$

We used orthogonality condition of functions of the considered series framework the heterostructure to calculate coefficients $a_{n\Phi\rho}$. The coefficients $a_{n\Phi\rho}$ could be calculated for any quantity of terms N. In the common case equations for the required coefficients could be written as

$$-\frac{L_x^2 L_y^2 L_z^2}{\pi^5}\sum_{n=1}^{N}\frac{a_{n\Phi I}}{n^6}e_{n\Phi I}(t)=-\frac{1}{2\pi L_x}\sum_{n=1}^{N}\int_0^t\int_0^{L_x}[1-c_n(2x)]\int_0^{L_y}\left\{L_y+y\,s_n(2y)+\frac{L_y}{2\pi n}[c_n(2y)-1]\right\}\times$$

$$\times\frac{a_{n\Phi I}}{n^2}\int_0^{L_z}D_{\Phi I}(x,y,z,T)\left\{z\,s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\,e_{n\Phi I}(\tau)\,d\,\tau-\frac{1}{2\pi}\sum_{n=1}^{N}\int_0^t\int_0^{L_x}\{x\,s_n(2x)+$$

$$+L_x+\frac{L_x}{2\pi n}[c_n(2x)-1]\Big\}\int_0^{L_y}[1-c_n(2y)]\int_0^{L_z}D_{\Phi I}(x,y,z,T)\left\{z\,s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}d\,z\,d\,y\,d\,x\times$$

$$\times a_{n\Phi I}\frac{e_{n\Phi I}(\tau)}{n^2 L_y}d\,\tau-\frac{1}{2\pi L_x}\sum_{n=1}^{N}\frac{a_{n\Phi I}}{n^2}\int_0^t\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{y\,s_n(2y)+\frac{L_y}{2\pi n}[c_n(2y)-1]+\right.$$

$$\left.+L_y\right\}\int_0^{L_z}[1-c_n(2y)]D_{\Phi I}(x,y,z,T)d\,z\,d\,y\,d\,x\,e_{n\Phi I}(\tau)d\,\tau+\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi I}}{n^3}\int_0^t e_{n\Phi I}(\tau)\int_0^{L_x}\left\{\frac{L_x}{2\pi n}[c_n(x)-1]+\right.$$

$$\left.+x\,s_n(x)\right\}\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}I^2(x,y,z,t)k_{I,I}(x,y,z,T)\left\{\frac{L_z}{2\pi n}[c_n(z)-1]+\right.$$

$$\left.+z\,s_n(z)\right\}d\,z\,d\,y\,d\,x-\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi I}}{n^3}\int_0^t e_{n\Phi I}(\tau)\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{\frac{L_y}{2\pi n}[c_n(y)-1]+\right.$$

$$\left.+y\,s_n(y)\right\}\int_0^{L_z}\left\{z\,s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}k_I(x,y,z,T)I\,(x,y,z,t)d\,z\,d\,y\,d\,x+\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi I}}{n^3}\times$$

$$\times\int_0^t e_{n\Phi I}(\tau)\int_0^{L_x}\left\{x\,s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{y\,s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}\left\{\frac{L_z}{2\pi n}[c_n(z)-1]+\right.$$

$$+ z s_n(z)\}f_{\Phi I}(x,y,z)\,d z\,d y\,d x$$

$$-\frac{L_x^2 L_y^2 L_z^2}{\pi^5}\sum_{n=1}^{N}\frac{a_{n\Phi V}}{n^6}e_{n\Phi V}(t)=-\frac{1}{2\pi L_x}\sum_{n=1}^{N}\int_0^t\int_0^{L_x}[1-c_n(2x)]\int_0^{L_y}\left\{L_y+y s_n(2y)+\frac{L_y}{2\pi n}[c_n(2y)-1]\right\}\times$$

$$\times\frac{a_{n\Phi V}}{n^2}\int_0^{L_z}D_{\Phi V}(x,y,z,T)\left\{z s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}d z\,d y\,d x\,e_{n\Phi V}(\tau)\,d\tau-\frac{1}{2\pi}\sum_{n=1}^{N}\int_0^t\int_0^{L_x}\{x s_n(2x)+$$

$$+L_x+\frac{L_x}{2\pi n}[c_n(2x)-1]\Big\}\int_0^{L_y}[1-c_n(2y)]\int_0^{L_z}D_{\Phi V}(x,y,z,T)\left\{z s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}d z\,d y\,d x\times$$

$$\times a_{n\Phi V}\frac{e_{n\Phi V}(\tau)}{n^2 L_y}d\tau-\frac{1}{2\pi L_x}\sum_{n=1}^{N}\frac{a_{n\Phi V}}{n^2}\int_0^t\int_0^{L_x}\left\{x s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{y s_n(2y)+\frac{L_y}{2\pi n}[c_n(2y)-1]+\right.$$

$$\left.+L_y\right\}\int_0^{L_z}[1-c_n(2y)]D_{\Phi V}(x,y,z,T)\,d z\,d y\,d x\,e_{n\Phi V}(\tau)d\tau+\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi V}}{n^3}\int_0^t e_{n\Phi V}(\tau)\int_0^{L_x}\left\{\frac{L_x}{2\pi n}[c_n(x)-1]+\right.$$

$$\left.+x s_n(x)\right\}\int_0^{L_y}\left\{y s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}V^2(x,y,z,t)\,k_{V,V}(x,y,z,T)\left\{\frac{L_z}{2\pi n}[c_n(z)-1]+\right.$$

$$\left.+z s_n(z)\right\}d z\,d y\,d x-\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi V}}{n^3}\int_0^t e_{n\Phi V}(\tau)\int_0^{L_x}\left\{x s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{\frac{L_y}{2\pi n}[c_n(y)-1]+\right.$$

$$\left.+y s_n(y)\right\}\int_0^{L_z}\left\{z s_n(z)+\frac{L_z}{2\pi n}[c_n(z)-1]\right\}k_V(x,y,z,T)V(x,y,z,t)\,d z\,d y\,d x+\frac{1}{\pi^3}\sum_{n=1}^{N}\frac{a_{n\Phi V}}{n^3}\times$$

$$\times\int_0^t e_{n\Phi V}(\tau)\int_0^{L_x}\left\{x s_n(x)+\frac{L_x}{2\pi n}[c_n(x)-1]\right\}\int_0^{L_y}\left\{y s_n(y)+\frac{L_y}{2\pi n}[c_n(y)-1]\right\}\int_0^{L_z}\left\{\frac{L_z}{2\pi n}[c_n(z)-1]+\right.$$

$$\left.+z s_n(z)\right\}f_{\Phi V}(x,y,z)\,d z\,d y\,d x\,.$$

3. DISCUSSION

In the present paper we analyzed redistribution of infused and implanted dopants in heterostructure, which have been presented on Fig. 1. The analysis has been done by using relations, calculated in the previous section. First of all we consider situation, when dopant diffusion coefficient in doped area is larger, than in nearest areas. It has been shown, that in this case distribution of concentration of dopant became more compact in comparison with wise versa situation (see Figs. 2 and 3 for diffusion and ion types of doping). In the wise versa situation (when dopant diffusion coefficient in doped area is smaller, than in nearest areas) we obtained spreading of distribution of concentration of dopant. In this case outside of doping material one can find higher spreading in comparison with wise versa situation (see Fig. 4).

It should be noted, that properties of layers of multilayer structure varying in space: varying layers with larger and smaller values of the diffusion coefficient. In this situation with account results, which shown on Figs. 2-4, layers of the considered heterostructure with smaller value of dopant should has smaller level of doping in comparison with nearest layers to exclude changing of type of doping in the nearest layers. For a more complete doping of each section and at the same to decrease diffusion of dopant into nearest sections it is attracted an interest optimization of annealing of dopant and /or radiation defects. Let us optimize annealing of dopant and/or radiation defects by using recently introduce criterion [18-23]. Framework the criterion we approximate real distribution of concentration of dopant by idealized step-wise distribution of concentration $\psi(x,y,z)$ (see Figs. 5 and 6 for diffusive or ion types of doping). Farther we determine optimal annealing time by minimization of mean-squared error

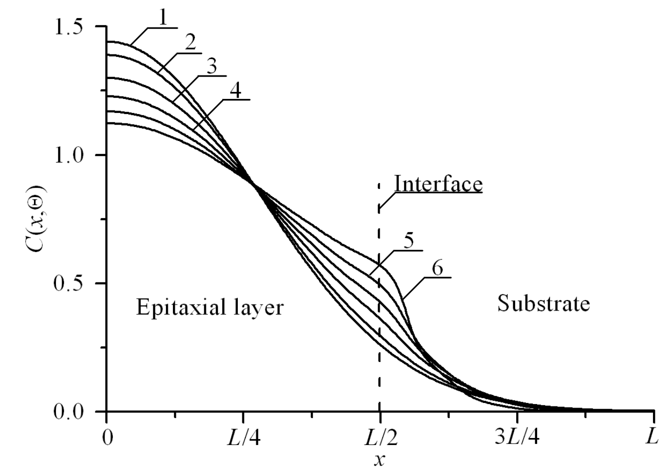

Fig.2. Spatial distributions of infused dopant concentration in the considered heterostructure.

The considered direction perpendicular to the interface between epitaxial layer substrate. Difference between values of dopant diffusion coefficient in layers of heterostructure increases with increasing of number of curves

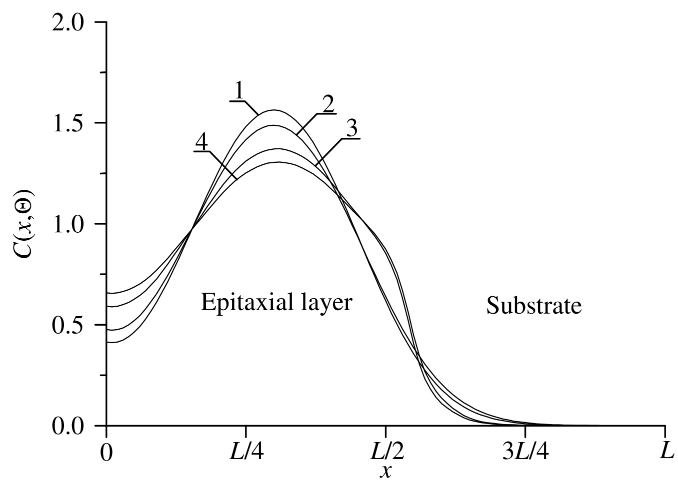

Fig.3. Spatial distributions of infused dopant concentration in the considered heterostructure.

Curves 1 and 3 corresponds to annealing time $\Theta=0.0048(L_x^2+L_y^2+L_z^2)/D_0$. Curves 2 and 4 corresponds to annealing time $\Theta=0.0057(L_x^2+L_y^2+L_z^2)/D_0$. Curves 1 and 2 corresponds to homogenous sample. Curves 3 and 4 corresponds to the considered heterostructure. Difference between values of dopant diffusion coefficient in layers of heterostructure increases with increasing of number of curves

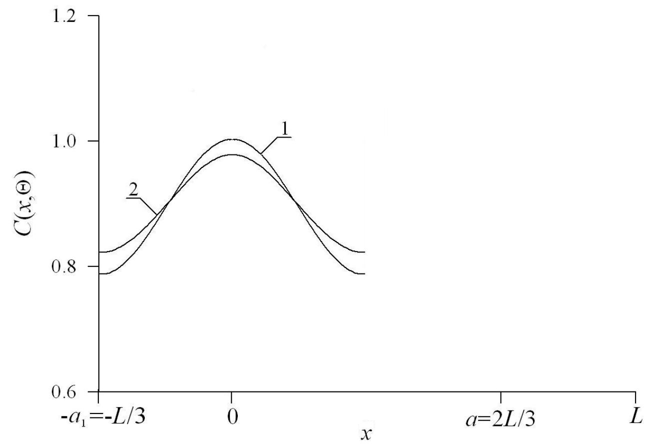

Fig.4. Implanted dopant distributions in heterostructure in heterostructure with two epitaxial layers (solid lines) and with one epitaxial layer (dushed lines) for different values of annealing time.

Difference between values of dopant diffusion coefficient in layers of heterostructure increases with increasing of number of curves

$$U=\frac{1}{L_x L_y L_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}\left[C\left(x,y,z,\Theta\right)-\psi\left(x,y,z\right)\right]d\,z\,d\,y\,d\,x\,. \tag{8}$$

Dependences of optimal annealing time are shown on Figs. 7 and 8 for diffusion and ion types of doping. It should be noted, that after finishing of ion doping of material it is necessary to anneal radiation defects. In the ideal case after finishing of the annealing dopant achieves nearest interface between materials of heterostructure. If the dopant has no time to achieve the interface, it is practicably to additionally anneal the dopant. The Fig. 8 shows dependences of the exactly additional annealing time of implanted dopant. Necessity of annealing of radiation defects leads to smaller values of optimal annealing time for ion doping in comparison with values of optimal annealing time for diffusion type of doping. Using diffusion type of doping did not leads to so large damage in comparison with damage during ion type of doping.

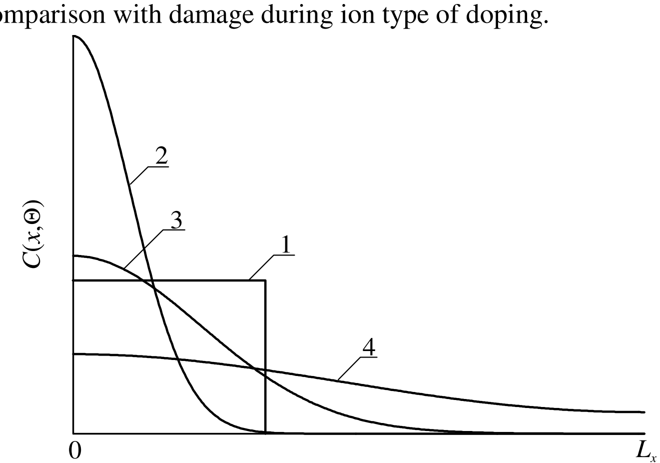

Fig. 5. Distributions of concentrations of infused dopant in the considered heterostructure.

Curve 1 is the idealized distribution of dopant. Curves 2-4 are the real distributions of concentrations of dopant for different values of annealing time for increasing of annealing time with increasing of number of curve

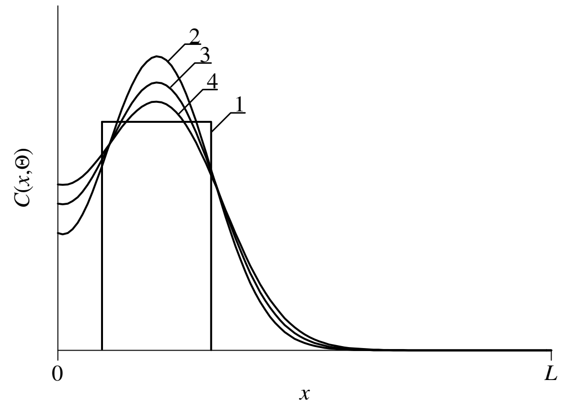

Fig. 6. Distributions of concentrations of implanted dopant in the considered heterostructure.

Curve 1 is the idealized distribution of dopant. Curves 2-4 are the real distributions of concentrations of dopant for different values of annealing time for increasing of annealing time with increasing of number of curve

Dependences of optimal annealing time are shown on Figs. 7 and 8 for diffusion and ion types of doping. It should be noted, that after finishing of ion doping of material it is necessary to anneal radiation defects. In the ideal case after finishing of the annealing dopant achieves nearest interface between materials of heterostructure. If the dopant has no time to achieve the interface, it is practicably to additionally anneal the dopant. The Fig. 8 shows dependences of the exactly additional annealing time of implanted dopant. Necessity of annealing of radiation defects leads to smaller values of optimal annealing time for ion doping in comparison with values of optimal annealing time for diffusion type of doping. Using diffusion type of doping did not leads to so large damage in comparison with damage during ion type of doping.

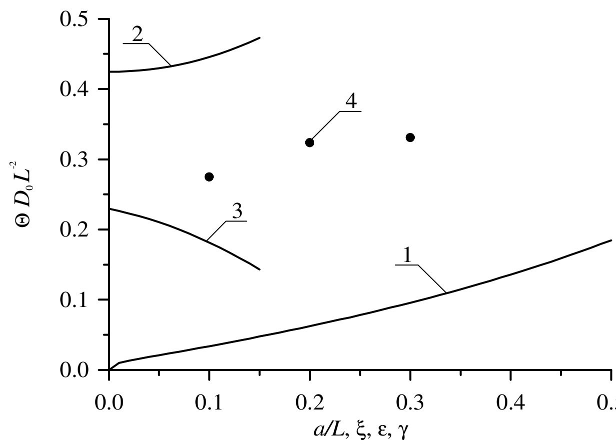

Fig.7. Optimal annealing time of infused dopant as dependences of several parameters.

Curve 1 is the dependence of the considered annealing time on dimensionless thickness of epitaxial layer a/L and $\xi=\gamma=0$ for equal to each other values of dopant diffusion coefficient in all parts of heterostructure. Curve 2 is the dependence of the considered annealing time on the parameter ε for a/L=1/2 and $\xi=\gamma=0$. Curve 3 is the dependence of the considered annealing time on the parameter ξ for a/L=1/2 and $\varepsilon=\gamma=0$. Curve 4 is the dependence of the considered annealing time on parameter γ for a/L=1/2 and $\varepsilon=\xi=0$

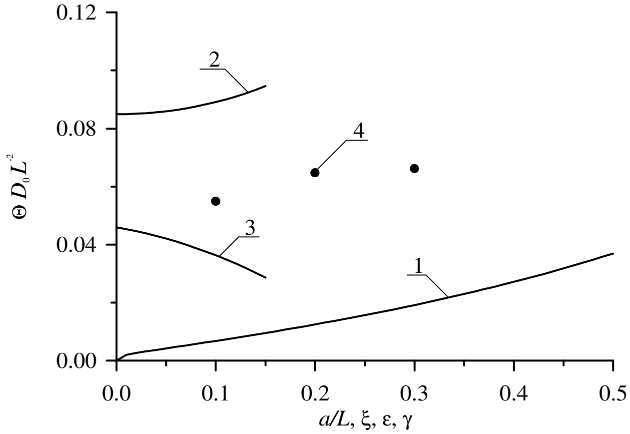

Fig.8. Optimal annealing time of implanted dopant as dependences of several parameters.

Curve 1 is the dependence of the considered annealing time on dimensionless thickness of epitaxial layer a/L and $\xi=\gamma=0$ for equal to each other values of dopant diffusion coefficient in all parts of heterostructure. Curve 2 is the dependence of the considered annealing time on the parameter ε for a/L=1/2 and $\xi=\gamma=0$. Curve 3 is the dependence of the considered annealing time on the parameter ξ for a/L=1/2 and $\varepsilon=\gamma=0$. Curve 4 is the dependence of the considered annealing time on parameter γ for a/L=1/2 and $\varepsilon=\xi=0$

4. CONCLUSIONS

In this paper we introduced an approach to manufacture of field-effect of transistors which gives a possibility to decrease their dimensions. The decreasing based on manufacturing the transistors in a heterostructure with specific configuration, doping of required areas of the heterostructure by diffusion or ion implantation and optimization of annealing of dopant and/or radiation defects. Framework the approach we introduce an approach of additional doping of channel. The additional doping gives us possibility to modify energy band diagram. We also consider an analytical approach to model and optimize technological process.

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REFERENCES

1. J.Y. Fang, G.Y. Lee, J.I. Chyi, C.P. Hsu, Y.W. Kang, K.C. Fang, W.L. Kao, D.J. Yao, C.H. Hsu, Y.F. Huang, C.C. Chen, S.S. Li, J.A. Yeh, F. Ren, Y.L. Wang. Viscosity-dependent drain current noise of AlGaN/GaN high electron mobility transistor in polar liquids. J. Appl. Phys. Vol. 114 (20). P. 204503-204507 (2013).
2. G. Volovich. Modern chips UM3Ch class D manufactured by firm MPS. Modern Electronics. Issue 2. P. 10-17 (2006).
3. A. Kerentsev, V. Lanin. Constructive-technological features of MOSFET-transistors. Power Electronics. Issue 1. P. 34-38 (2008).
4. A.O. Ageev, A.E. Belyaev, N.S. Boltovets, V.N. Ivanov, R.V. Konakova, Ya.Ya. Kudrik, P.M. Litvin, V.V. Milenin, A.V. Sachenko. Au–TiBx−n-6H-SiC Schottky barrier diodes: the features of current flow in rectifying and nonrectifying contacts. Semiconductors. Vol. 43 (7). P. 897-903 (2009).

5. C. Senthilpari, K. Diwakar, A.K. Singh. Low Energy, Low Latency and High Speed Array Divider Circuit Using a Shannon Theorem Based Adder Cell. Recent Patents on Nanotechnology. Vol. 3 (1). P. 61-72 (2009).
6. M.M. Fouad, H.H. Amer, A.H. Madian, M.B. Abdelhalim. Current Mode Logic Testing of XOR/XNOR Circuit: A Case Study. Circuits and Systems. Vol. 4 (4). P. 364-368 (2013).
7. S.A. Chachuli, P.N.A. Fasyar, N. Soin, N.M. Karim, N. Yusop. Pareto ANOVA analysis for CMOS 0.18 µm two-stage Op-amp. Mat. Sci. Sem. Proc. Vol. 24. P. 9-14 (2014).
8. M.J. Kumar, T.V. Singh. Quantum confinement effects in strained silicon MOSFETs MOSFETs. Int. J. Nanoscience. Vol. 7 (2-3). P. 81-84 (2008).
9. D. Fathi, B. Forouzandeh. Accurate analysis of global interconnects in nano-FPGAs. Nano. Vol. 4 (3). P. 171-176 (2009).
10. D. Fathi, B. Forouzandeh, N. Masoumi. New enhanced noise analysis in active mixers in nanoscale technologies. Nano. Vol. 4 (4). P. 233-238 (2009).
11. Jung-Hui Tsai, Shao-Yen Chiu, Wen-Shiung Lour, Der-Feng Guo. High-performance InGaP/GaAs pnp δ-doped heterojunction bipolar transistor. Semiconductors. T. 43 (7). C. 971-974 (2009).
12. V.I. Lachin, N.S. Savelov. Electronics (Phoenix, Rostov-na-Donu (2001).
13. N.A. Avaev, Yu.E. Naumov, V.T. Frolkin. Basis of microelectronics (Radio and communication, Moscow, 1991).
14. Z.Yu. Gotra. Technology of microelectronic devices (Radio and communication, Moscow, 1991).
15. V.L. Vinetskiy, G.A. Kholodar', Radiative physics of semiconductors. ("Naukova Dumka", Kiev, 1979, in Russian).
16. P.M. Fahey, P.B. Griffin, J.D. Plummer. Point defects and dopant diffusion in silicin. Rev. Mod. Phys. Vol. 61. № 2. P. 289-388 (1989).
17. M.L. Krasnov, A.I. Kiselev, G.I. Makarenko. Integral equations ("Science", Moscow, 1976).
18. E.L. Pankratov. Dopant diffusion dynamics and optimal diffusion time as influenced by diffusion-coefficient nonuniformity. Russian Microelectronics. 2007. V.36 (1). P. 33-39.
19. E.L. Pankratov. Redistribution of dopant during annealing of radiative defects in a multilayer structure by laser scans for production an implanted-junction rectifiers. Int. J. Nanoscience. Vol. 7 (4-5). P. 187–197 (2008).
20. E.L. Pankratov. Decreasing of depth of implanted-junction rectifier in semiconductor heterostructure by optimized laser annealing. J. Comp. Theor. Nanoscience. Vol. 7 (1). P. 289-295 (2010).
21. E.L. Pankratov, E.A. Bulaeva. Application of native inhomogeneities to increase com pactness of vertical field-effect transistors. J. Comp. Theor. Nanoscience. Vol. 10 (4). P. 888-893 (2013).
22. E.L. Pankratov, E.A. Bulaeva. An approach to manufacture of bipolar transistors in thin film structures. On the method of optimization. Int. J. Micro-Nano Scale Transp. Vol. 4 (1). P. 17-31 (2014).
23. E.L. Pankratov, E.A. Bulaeva. Increasing of sharpness of diffusion-junction heterorectifier by using radiation processing. Int. J. Nanoscience. Vol. 11 (5). P. 1250028-1250035 (2012).

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