OPTIMIZATION OF DOPANT DIFFUSION AND ION IMPLANTATION TO INCREASE INTEGRATION RATE OF FIELD-EFFECT HETEROTRANSISTORS. AN APPROACH TO SIMPLIFY CONSTRUCTION OF THE HETEROTRANSISTORS

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ABSTRACT

In this work we introduce an approach to decrease dimensions of a field-effect heterotransistors. The approach based on manufacturing field-effect transistors in heterostructures and optimization of technological processes. At the same time we consider possibility to simplify their constructions.

KEYWORDS

Field-effect heterotransistors; simplification of construction of heterotransistors; increasing integration rate of transistors; optimization of manufacturing of heterotransistors; analytical modelling of technological process

1. INTRODUCTION

One of the actual questions of the solid state electronics is increasing of integration rate of elements of integrated circuits [1-14]. At the same time with decreasing of integration rate of elements of integrated circuits one can find decreasing of dimensions of the elements. In the present time it is known several approaches to decrease dimensions of elements of integrated circuits and their discrete analogs. Two of them are laser and microwave types of annealing of dopants and radiation defects [15-17]. Using this approaches leads to generation inhomogenous distribution of temperature in annealed materials. Just this inhomogeneity leads to decreasing dimensions of elements of integrated circuits and their discrete analogs. Another approach to decrease the above dimensions is doping required areas of epitaxial layers of heterostructures by dopant diffusion or ion implantation. However optimization of annealing of dopant and/or radiation defects is required in this case [18,19]. It is also attracted an interest radiation processing of doped materials. The processing leads to changing distribution of concentration of dopants [20]. The changing could also leads to decrease dimensions of elements of integrated circuits and their discrete analogs [21-23].

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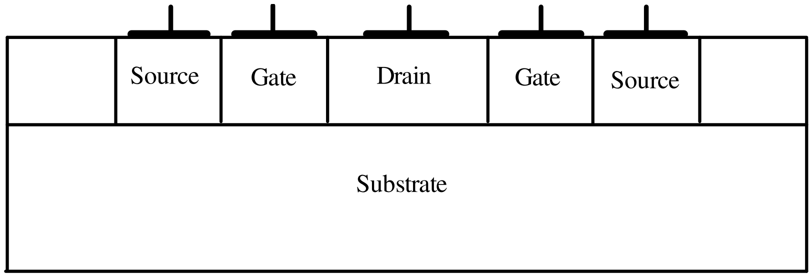

Fig. 1. Heterostructure, which consist of a substrate and epitaxial layer with several sections. Structure in deep of heterostructure

In this paper we analysed redistribution of concentration of dopant with account redistribution of radiation defects in the considered heterostructure, which is presented in Fig. 1. Some sections have been manufactured in epitaxial layer so, as it is shown in the Fig. 1. Dopants have been infused or implanted in the sections to produce required types of conductivity (*n* or *p*). Farther annealing of dopant and/or radiation defects should be annealed. Main aim of our paper is analysis of dynamic of redistribution of dopant and radiation defects in considered heterostructure during annealing.

2. METHOD OF SOLUTION

To solve our aims we determine spatio-temporal distribution of concentration of dopant. To determine the distribution one shall solve the following equation [1,3-5]

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

Boundary and initial conditions for the equation are

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

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

The function $C(x,y,z,t)$ describes the spatio-temporal distribution of concentration of dopant; T is the temperature of annealing; D_C is the dopant diffusion coefficient. Dopant diffusion coefficient is different in different materials. The diffusion coefficient is also depends on temperature of annealing with account Arrhenius law. Dependences of dopant diffusion coefficients could be approximated by the following function [3,24-26]

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

The multiplier $D_L(x,y,z,T)$ depends on coordinate and temperature (due to Arrhenius law); $P(x,y,z,T)$ is the limit of solubility of dopant; the parameter γ is different in different materials and should be integer in the following interval $\gamma\in[1,3]$ [3]; the function $V(x,y,z,t)$ describes the spatio-temporal distribution of concentration of radiation vacancies; parameter V^* describes the equilibrium concentration of vacancies. Dependence of dopant diffusion coefficient on concentration has been described in details in [3]. It should be noted, that diffusive type of doping did not leads to radiation damage of materials and $\zeta_1=\zeta_2=0$. We determine spatio-temporal distributions of concentrations point radiation defects by solving the following system of equations [25,26]

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

with boundary and boundary conditions

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

Here $\rho=I,V$; the function $I(x,y,z,t)$ describes the spatio-temporal distribution of concentration of interstitials; $D_\rho(x,y,z,T)$ are the diffusion coefficients of vacancies and interstitials; terms $V^2(x,y,z,t)$ and $I^2(x,y,z,t)$ corresponds to generation of divacancies and diinterstitials, respectively; $k_{I,V}(x,y,z,T)$, $k_{I,I}(x,y,z,T)$ and $k_{V,V}(x,y,z,T)$ are the parameters of recombination of point radiation defects and generation their complexes, respectively.

Spatio-temporal distributions of concentrations of simplest complexes of radiation defects (divacancies $\Phi_V(x,y,z,t)$ and diinterstitials $\Phi_I(x,y,z,t)$) have been determine by solving by solving the following system of equations [25,26]

$$\begin{cases} \frac{\partial \Phi_I(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial y}\right]+ \\ +\frac{\partial}{\partial z}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial z}\right]+k_{I,I}(x,y,z,T)\,I^2(x,y,z,t)-k_I(x,y,z,T)\,I(x,y,z,t) \\ \frac{\partial \Phi_V(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial y}\right]+ \\ +\frac{\partial}{\partial z}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_V(x,y,z,t)}{\partial z}\right]+k_{V,V}(x,y,z,T)V^2(x,y,z,t)-k_V(x,y,z,T)V(x,y,z,t) \end{cases} \tag{6}$$

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

with boundary and initial conditions

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

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

Here $D_{\Phi I}(x,y,z,T)$ and $D_{\Phi V}(x,y,z,T)$ are diffusion coefficients of diinterstitials and divacancies; $k_I(x,y,z,T)$ and $k_V(x,y,z,T)$ are parameters of decay of complexes.

It should be noted, that nonlinear equations with space and time varying coefficients are usually used to describe physical processes. Although the equations are usually solved in different limiting cases [27-30]. Spatio-temporal distribution of concentration of dopant have been calculated by using method of averaging of function corrections [21,31] with decreased quantity of iteration steps [32]. Framework this approach we used solutions of the above differential equations without any nonlinearity and with averaged values of diffusion coefficients and thermal diffusivity D_{0L}, D_{0I}, D_{0V}, $D_{0\Phi I}$, $D_{0\Phi V}$, α_0. The solutions could be written as

$$C_1(x,y,z,t)=\frac{1}{L_xL_yL_z}+\frac{2}{L_xL_yL_z}\sum_{n=1}^{\infty}F_{nC}c_n(x)c_n(y)c_n(z)e_{nC}(t),$$

$$I_1(x,y,z,t)=\frac{1}{L_xL_yL_z}+\frac{2}{L_xL_yL_z}\sum_{n=1}^{\infty}F_{nI}c_n(x)c_n(y)c_n(z)e_{nI}(t),$$

$$V_1(x,y,z,t)=\frac{1}{L_xL_yL_z}+\frac{2}{L_xL_yL_z}\sum_{n=1}^{\infty}F_{nC}c_n(x)c_n(y)c_n(z)e_{nV}(t),$$

$$\Phi_{I1}(x,y,z,t)=\frac{1}{L_xL_yL_z}+\frac{2}{L_xL_yL_z}\sum_{n=1}^{\infty}F_{n\Phi_I}c_n(x)c_n(y)c_n(z)e_{n\Phi_I}(t),$$

$$\Phi_{V1}(x,y,z,t)=\frac{1}{L_xL_yL_z}+\frac{2}{L_xL_yL_z}\sum_{n=1}^{\infty}F_{n\Phi_V}c_n(x)c_n(y)c_n(z)e_{n\Phi_V}(t),$$

where $e_{n\rho}(t)=\exp\left[-\pi^2n^2D_{0\rho}t\left(\frac{1}{L_x^2}+\frac{1}{L_y^2}+\frac{1}{L_z^2}\right)\right]$, $F_{n\rho}=\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}c_n(w)\,f_\rho(u,v,w)\,d\,w\,d\,v\,d\,u$, $c_n(\chi)=\cos(\pi n\chi/L_\chi)$.

The second-order approximations and approximations with higher orders of concentration of dopant, concentrations of radiation defects and temperature have been calculated framework standard iteration procedure of method of averaging of function corrections [21,31,32]. Framework the approach to calculate n-th-order approximations of the above concentrations and temperature we replace the required functions $C(x,y,z,t)$, $I(x,y,z,t)$, $V(x,y,z,t)$, $\Phi_I(x,y,z,t)$ and $\Phi_V(x,y,z,t)$ in the right sides of Eqs. (1), (4), (6) on the following sums $\alpha_{n\rho}+\rho_{n-1}(x,y,z,t)$. The replacement gives us possibility to obtain the following equations for the second-order approximation of above concentrations

$$\frac{\partial C_2(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left(D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,t)}{V^*}+\varsigma_2\frac{V^2(x,y,z,t)}{(V^*)^2}\right]\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,t)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\times\right.$$
$$\left.\times\frac{\partial C_1(x,y,z,t)}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,t)}{V^*}+\varsigma_2\frac{V^2(x,y,z,t)}{(V^*)^2}\right]\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,t)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\frac{\partial C_1(x,y,z,t)}{\partial y}+\right. \quad (8)$$
$$+\frac{\partial}{\partial z}\left(D_L(x,y,z,T)\frac{\partial C_1(x,y,z,t)}{\partial z}\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,t)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\left[1+\varsigma_2\frac{V^2(x,y,z,t)}{(V^*)^2}+\varsigma_1\frac{V(x,y,z,t)}{V^*}\right]\right)$$

$$\begin{cases}\frac{\partial I_2(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial y}\right]+\\ +\frac{\partial}{\partial z}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)][\alpha_{2V}+V_1(x,y,z,t)]-\\ -k_{I,I}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)]^2\\ \frac{\partial V_2(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial y}\right]+\\ +\frac{\partial}{\partial z}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)][\alpha_{2V}+V_1(x,y,z,t)]-\\ -k_{V,V}(x,y,z,T)[\alpha_{2V}+V_1(x,y,z,t)]^2\end{cases} \quad (9)$$

$$\begin{cases}\frac{\partial \Phi_{I2}(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial x}\right]+\\ +\frac{\partial}{\partial z}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial z}\right]+k_{I,I}(x,y,z,T)\,I^2(x,y,z,t)-k_I(x,y,z,T)I(x,y,z,t)\\ \frac{\partial \Phi_{V2}(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial x}\right]+\\ +\frac{\partial}{\partial z}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial z}\right]+k_{V,V}(x,y,z,T)\,V^2(x,y,z,t)-k_V(x,y,z,T)\,V(x,y,z,t)\end{cases} \quad (10)$$

Farther we obtain the second-order approximations of concentrations of dopant and radiation defects by integration of the left and right sides of the Eqs. (8)-(10)

$$C_2(x,y,z,t)=\frac{\partial}{\partial x}\left(\int_0^t D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,\tau)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\times\right.$$
$$\left.\times\frac{\partial C_1(x,y,z,\tau)}{\partial x}\right)d\tau+\frac{\partial}{\partial y}\left(\int_0^t\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,\tau)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\times\right.$$
$$\left.\times D_L(x,y,z,T)\frac{\partial C_1(x,y,z,\tau)}{\partial y}\right)+\frac{\partial}{\partial z}\left(\int_0^t\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]\frac{\partial C_1(x,y,z,\tau)}{\partial y}\times\right.$$

$$\times D_L(x,y,z,T)\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,\tau)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\Bigg)+f_C(x,y,z) \tag{8a}$$

$$\begin{cases} I_2(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial y}d\tau\right]+ \\ +\frac{\partial}{\partial z}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial z}d\tau\right]-\int_0^t k_{I,I}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)]^2 d\tau+f_I(x,y,z)- \\ -\int_0^t k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)]\,[\alpha_{2V}+V_1(x,y,z,\tau)]d\tau \\ V_2(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial y}d\tau\right]+ \\ +\frac{\partial}{\partial z}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial z}d\tau\right]-\int_0^t k_{V,V}(x,y,z,T)[\alpha_{2V}+V_1(x,y,z,\tau)]^2 d\tau+f_V(x,y,z)- \\ -\int_0^t k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)]\,[\alpha_{2V}+V_1(x,y,z,\tau)]d\tau \end{cases} \tag{9a}$$

$$\begin{cases} \Phi_{I2}(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial y}d\tau\right]+ \\ +\frac{\partial}{\partial z}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial z}d\tau\right]+f_{\Phi I}(x,y,z)+\int_0^t k_{I,I}(x,y,z,T)\,I^2(x,y,z,\tau)d\tau- \\ -\int_0^t k_I(x,y,z,T)\,I(x,y,z,\tau)\,d\tau \\ \Phi_{V2}(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial y}d\tau\right]+ \\ +\frac{\partial}{\partial z}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial z}d\tau\right]+f_{\Phi V}(x,y,z)+\int_0^t k_{V,V}(x,y,z,T)\,V^2(x,y,z,\tau)d\tau- \\ -\int_0^t k_V(x,y,z,T)\,V(x,y,z,\tau)\,d\tau \end{cases} \tag{10a}$$

We determine average values of the second-order approximations of the required functions by using the following standard relations [21,31,32]

$$\alpha_{2\rho}=\frac{1}{\Theta L_x L_y L_z}\int_0^\Theta\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}[\rho_2(x,y,z,t)-\rho_1(x,y,z,t)]\,d\,z\,d\,y\,d\,x\,d\,t\,. \tag{11}$$

Relations for the average values $\alpha_{2\rho}$ could be obtain by substitution of the second-order approximations of the considered concentrations (8*a*)-(10*a*) and their the first-order approximations into the relation (11)

$$\alpha_{2C}=\frac{1}{L_x L_y L_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z} f_C(x,y,z)\,d\,z\,d\,y\,d\,x\,, \tag{12}$$

$$\begin{cases}\alpha_{2I}=\dfrac{1}{2A_{II00}}\left\{\left(1+A_{IV01}+A_{II10}+\alpha_{2V}A_{IV00}\right)^2-4A_{II00}\left[\alpha_{2V}A_{IV10}-\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x-A_{II20}+\right.\right.\\ \left.\left.+A_{IV11}\right]\right\}^{\frac{1}{2}}-\dfrac{1+A_{IV01}+A_{II10}+\alpha_{2V}A_{IV00}}{2A_{II00}}\\ \alpha_{2V}=\dfrac{1}{2B_4}\sqrt{\dfrac{(B_3+A)^2}{4}-4B_4\left(y+\dfrac{B_3y-B_1}{A}\right)}-\dfrac{B_3+A}{4B_4},\end{cases} \tag{13}$$

where $A_{abij}=\dfrac{1}{\Theta L_xL_yL_z}\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}k_{a,b}(x,y,z,T)\;I_1^i(x,y,z,t)V_1^j(x,y,z,t)\,d\,z\,d\,y\,d\,x\,d\,t$, $B_4=A_{IV00}^2\times$ $\times A_{IV00}^2-2\left(A_{IV00}^2-A_{II00}A_{VV00}\right)^2$, $B_3=A_{IV00}A_{IV00}^2+A_{IV01}A_{IV00}^3+A_{IV00}A_{II10}A_{IV00}^2+4\left(A_{II00}A_{VV00}+\right.$ $\left.+A_{IV00}^2\right)\left[2A_{IV01}A_{IV00}+2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)\right]-4A_{IV10}A_{II00}A_{IV00}^2+$ $+2A_{IV00}A_{IV01}A_{IV00}^2$, $B_2=\left\{A_{IV00}^2A_{IV01}^2-4\left[A_{IV11}-A_{II20}-\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x\right]\times\right.$ $\times 4A_{II00}+\left(1+A_{IV01}+A_{II10}\right)^2+2A_{IV00}A_{IV01}\left(A_{IV00}A_{IV01}+A_{IV00}A_{II10}-4A_{IV10}A_{II00}+A_{IV00}\right)\Big\}A_{IV00}^2\big\{\left[2A_{IV01}A_{IV00}+\right.$ $+2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)\big]^2+2\left[\dfrac{2}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_V(x,y,z)\,d\,z\,d\,y\,d\,x+A_{IV01}\left(A_{II10}+\right.\right.$ $\left.+1+A_{IV01}\right]-2A_{II00}\left(A_{VV20}-A_{IV11}\right)+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\big]\left[2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)+\right.$ $\left.+2A_{IV01}A_{IV00}\right]\big\}$, $B_1=2A_{IV00}A_{IV01}\left(1+A_{IV01}+A_{II10}\right)^2-8\left[A_{IV11}-\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x-\right.$ $\left.-A_{II20}\right]A_{IV00}A_{IV01}A_{II00}+A_{IV01}^2\left(A_{IV00}+A_{IV00}A_{IV01}+A_{IV00}A_{II10}-4A_{IV10}A_{II00}\right)-2\left[\dfrac{2A_{II00}}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x+\right.$ $\left.+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{VV20}-A_{IV11}\right)+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\right]\left[2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-\right.$ $\left.-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)+2A_{IV01}A_{IV00}\right]$, $B_0=4A_{IV01}^2A_{II00}\left[\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x-\right.$ $\left.-A_{IV11}+A_{II20}\right]+A_{IV01}^2\left(A_{IV01}+A_{II10}+1\right)^2-\left[\dfrac{2A_{II00}}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_V(x,y,z)\,d\,z\,d\,y\,d\,x+\left(1+A_{IV01}+A_{II10}\right)\times\right.$ $\left.\times A_{IV01}-2A_{II00}\left(A_{VV20}-A_{IV11}\right)+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\right]^2$, $y=\sqrt[3]{\sqrt{q^2+p^3}-q}-\sqrt[3]{\sqrt{q^2+p^3}+q}+\dfrac{B_2}{6}$,

$q=\dfrac{B_2^3}{216}+\dfrac{B_0\left(4B_2-B_3^2\right)-B_1^2}{8}+\left(2B_1B_3-8B_0\right)\dfrac{B_2}{48}$, $p=\dfrac{B_1B_3}{12}-\dfrac{B_0}{3}-\dfrac{B_2^2}{36}$, $A=\sqrt{8y+B_3^2-4B_2}$,

$$\begin{cases}\alpha_{2\Phi_I}=A_{II20}-\dfrac{1}{\Theta L_xL_yL_z}\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}k_I(x,y,z,T)I(x,y,z,t)\,d\,z\,d\,y\,d\,x\,d\,t+\\ \qquad\qquad+\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_{\Phi I}(x,y,z)\,d\,z\,d\,y\,d\,x\\ \alpha_{2\Phi_V}=A_{VV20}-\dfrac{1}{\Theta L_xL_yL_z}\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}k_V(x,y,z,T)V(x,y,z,t)\,d\,z\,d\,y\,d\,x\,d\,t+\\ \qquad\qquad+\dfrac{1}{L_xL_yL_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}f_{\Phi V}(x,y,z)\,d\,z\,d\,y\,d\,x\end{cases} \tag{14}$$

Value of the parameter α_{2C} and final form of the appropriate equation depend on value of the parameter γ.

Farther we analyzed spatio-temporal distributions of concentrations of dopant and radiation defects by using their the second-order approximations. Usually the second-order approximations of calculated values gives us possibility to obtain main physical results.

3. DISCUSSION

In this section we analyzed dynamics of redistribution of dopant and radiation defects during annealing. The Figs. 2 and 3 show distributions of concentrations of infused and implanted dopants in heterostructure, which consist of two layers, respectively. In this case we consider doping of sections of epitaxial layer in situation, when dopant diffusion coefficient in doped materials is larger, than in nearest areas. The Figs. 2 and 3 show, that presents of interface between materials of heterostructure gives us possibility to manufacture more compact field-effect transistor in comparison with field-effect transistor in homogenous materials.

To increase compactness the considered field-effect transistor it is attracted an interest optimization of annealing of dopant and/or radiation defects. Reason of this optimization is rather homogenous distribution of dopant and unnecessary doping of materials of heterostructure outside the considered sections. During short-time annealing dopant can not achieves interface between materials of heterostructure. We optimize annealing time framework recently introduced criterion [18,19,21-23]. Framework the criterion we approximate real distributions of concentrations of dopants by step-wise functions. We minimize the following mean-squared error to estimate optimal values of annealing time

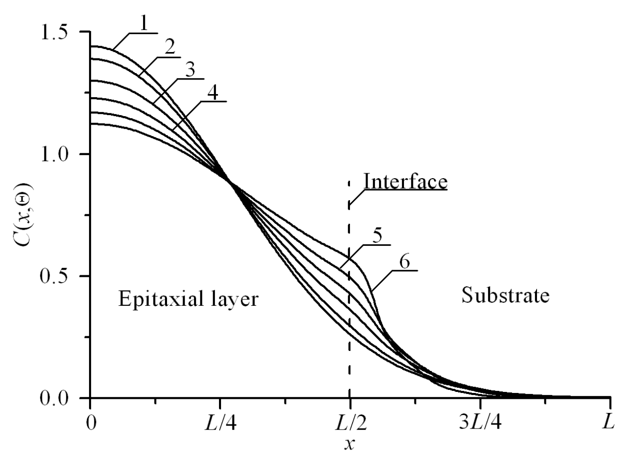

Fig.2. Typical distributions of concentration of dopant.

The dopant has been infused in the heterostructure from Fig. 1. The direction of the infusion is perpendicular to interface between epitaxial layer substrate. The distributions have been calculated under condition, when value of dopant diffusion coefficient in epitaxial layer is larger, than value of dopant diffusion coefficient in substrate. Increasing of number of curves corresponds to increasing of difference between values of dopant diffusion coefficient in layers of heterostructure

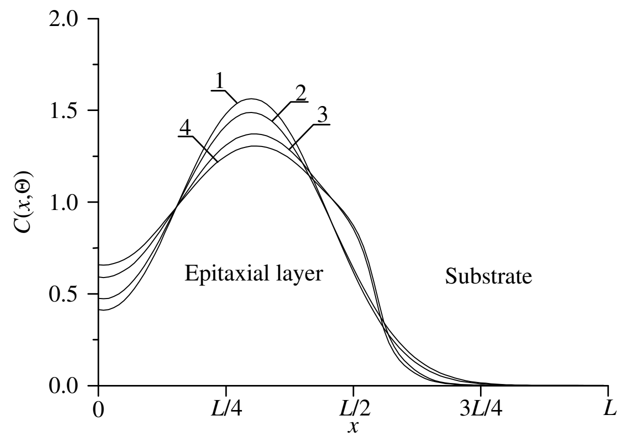

Fig.3. Typical distributions of concentration of dopant.

The dopant has been implanted in the heterostructure from Fig. 1. The direction of the implanted is perpendicular to interface between epitaxial layer substrate. The distributions have been calculated under condition, when value of dopant diffusion coefficient in epitaxial layer is larger, than value of dopant diffusion coefficient in substrate. Increasing of number of curves corresponds to increasing of difference between values of dopant diffusion coefficient in layers of 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 $\Theta=0.0057(L_x^2+ L_y^2+L_z^2)/D_0$.

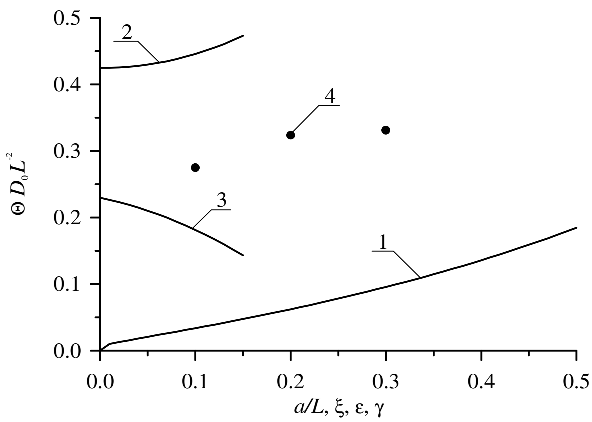

Fig.4. Optimized annealing time of infused dopant as functions of parameters.

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

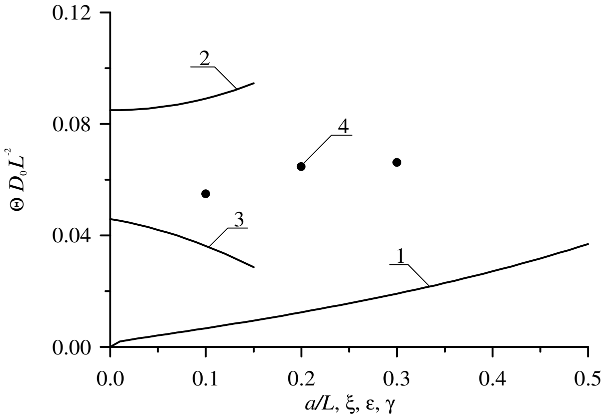

Fig.5. Optimized annealing time of implanted dopant as functions of parameters.

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

$$U=\frac{1}{L_x L_y L_z}\int\limits_0^{L_x}\int\limits_0^{L_y}\int\limits_0^{L_z}\left[C\left(x,y,z,\Theta\right)-\psi\left(x,y,z\right)\right]d\,z\,d\,y\,d\,x\,. \tag{15}$$

Here $\psi(x,y,z)$ is the idealised step-wise distribution of concentration of dopant, which would like to obtain for maximal decreasing of dimensions of transistors. Dependences of optimal values of annealing time are presented on Figs. 4 and 5 for diffusion and ion types of doping, respectively. It should be noted, that after finishing implantation of ions of dopant it is necessary to anneal of radiation of defects. It could be find spreading of distribution of dopant during the annealing. In the ideal case distribution of dopant achieves interface between materials of heterostructure during annealing of radiation defects. It is necessary to anneal dopant after finishing of annealing of radiation defects in the case, when the dopant did not achieves the interface between layers of heterostructure during annealing of radiation defects. In this situation optimal value of continuance of additional annealing is smaller, than continuance of annealing of infused dopant. It should be noted, that introduced approach to increase integration rate of field-effect transistors gives us possibility to simplify their common construction.

4. CONCLUSIONS

In this paper we introduce an approach to increase integration rate of field-effect heterotransistors. Framework the approach one should manufacture a heterostructure with special construction. After that appropriate areas of the heterostructure with account construction should be doped by diffusion or ion implantation. After the doping dopant and/or radiation defects should be annealed. It has been formulated a recommendation to optimize annealing to

The approach based on manufacture heterostructure with special construction, doping of required areas of heterostructure by dopant diffusion or ion implantation and optimization of annealing of dopant and/or radiation defects. The optimization of annealing gives us possibility to decrease dimensions of transistors with increasing their integration rate. At the same time one can obtain simplification of construction of integrated circuits.

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