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On increasing of integration rate of multi-channel heterotransistors

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ABSTRACT

In this paper we consider an approach to increase integration rate of foeld-effect heterotransistors. The approach based on manufacturing a heterostructure with required configuration, doping of required areas of the heterostructure by diffusion or ion implantation and optimized annealing of dopant and/or radiation defects. Framework this paper we consider a possibility to manufacture with several channels. Manufacturing multi-channel transistors gives us a possibility the to increase integration rate of transistors and to increase electrical current through the transistor.

INTRODUCTION

In the present time integration rate of elements of integrated circuits intensively increasing[1-7]. Increasing of the integration rate leads to necessity to decrease dimensions of these elements. To decrease these dimensions it is attracted an interest laser and microwave types of annealing[8-12]. It is also attracted an interest radiation processing of doped materials to solve the same problem[13,14].

In this paper we consider manufacturing a multi-channel heterotransistor with common gate. The heterostructure consist of a substrate and epitaxial layer. The epitaxial layer includes into itself several sections (see Figure 1). After manufacturing of the required quantity of channels they should be doped to generation required type of conductivity (n or p). Farther dopant and/or radiation defects should be annealed. Increasing of annealing time leads to increasing of quantity of dopant in nearest materials. Decreasing of annealing time give not possibility to organize full doping of channels of transistors. Main aim of the present paper is choosing of compromise value of annealing time to organize full doping of channels of transistors and at the same time to decrease quantity of dopant in nearest materials.

METHOD OF SOLUTION

To achieve our aim we determine spatio-temporal distributions of concentrations of dopant and radiation defects. We determine the required distribution of concentrations of dopant by solution of the following boundary problem

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

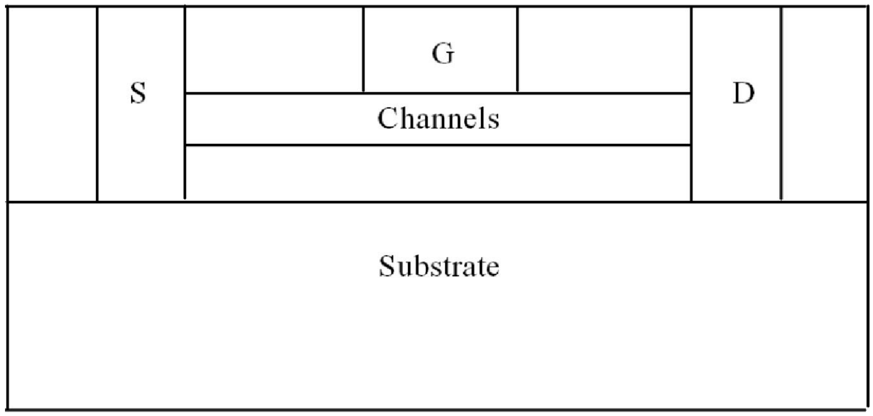

Figure 1a : Heterostructure which consist of a substrate and an epitaxial layer. Side view

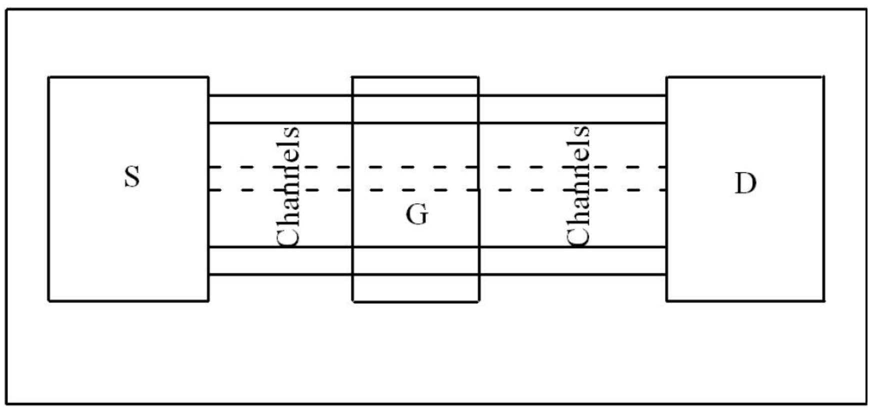

Figure 1b : Heterostructure which consist of a substrate and an epitaxial layer. Top view

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

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

Here C(x,y,z,t) is the spatio-temporal distribution of concentration of dopant; T is the temperature of annealing; D_c is the dopant diffusion coefficient. Value of dopant diffusion coefficient depends on properties of materials in layers of heterostructure, speed of heating and cooling of heterostructure (accounting for the Arrhenius law). Dependence of dopant diffusion coefficient on parameters could be approximated by the following relation[14-16]

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

where D_L (x,y,z,T) is the spatial (due to inhomogeneity of heterostructure) and temperature (due to Arrhenius law) dependences of dopant diffusion coefficient; P (x,y,z, T) is the limit of solubility of dopant; parameter γ depends on properties of materials and could be integer in the following interval $\gamma \in [1,3]$[15]; V (x,y,z,t) is the spatio- temporal distribution of concentration of dopant; V^* is the equilibrium distribution of distribution of vacancies. Reason of presents of radiation part in approximation (3) is generation of radiation vacancies. In this situation value of dopant diffusion coefficient increases. Now one can find coupling of

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redistribution of dopant and radiation defects. Concentrational dependence of dopant diffusion coefficient has been described in detailed in [15]. It should be noted, that using diffusion type of doping did not leads to generation radiation defects and $\zeta_1 = \zeta_2 = 0$.

We determine spatio- temporal distribution of concentration of radiation defects by solving the following boundary problem[14,16]

$$\frac{\partial I(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x}\left[D_I(x,y,z,T)\frac{\partial I(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_I(x,y,z,T)\frac{\partial I(x,y,z,t)}{\partial y}\right] +$$

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

$$-k_{I,I}(x,y,z,T)I^2(x,y,z,t) \tag{4}$$

$$\frac{\partial V(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x}\left[D_V(x,y,z,T)\frac{\partial V(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_V(x,y,z,T)\frac{\partial V(x,y,z,t)}{\partial y}\right] +$$

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

$$-k_{V,V}(x,y,z,T)V^2(x,y,z,t)$$

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

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

We determine spatio-temporal distribution of concentrations of divacancies Φ_V (x, y,z,t) and diinterstitials Φ_I (x,y,z,t) by solution of the following boundary problem[14, 16]

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

$$+\frac{\partial}{\partial y}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_I(x,y,z,t)}{\partial z}\right] -$$

$$-k_I(x,y,z,T)I(x,y,z,t) \tag{6}$$

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

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

$$-k_V(x,y,z,T)V(x,y,z,t)$$

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

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

Φ_I (x,y,z,0)=$f_{\Phi I}$ (x,y,z), Φ_V (x,y,z,0)=$f_{\Phi V}$ (x,y,z). **(7)**

Here $D_{\Phi\rho}$(x,y,z,T) are the diffusion coefficients of complexes of radiation defects; k_ρ(x,y,z,T) are the parameters of decay of the above complexes.

We determine spatio-temporal distribution of concentrations of dopant and radiation defects by method of averaging of function corrections[17-19] with decreasing quantity of iteration steps[18]. Framework the approach we used solutions of Eqs. (1), (4), (6) with averaged values of diffusion coefficients D_{0L}, D_{0I}, D_{0V}, $D_{0\Phi I}$, $D_{0\Phi V}$, zero values of parameters of recombination of radiation defects and parameters of generation and decay of their complexes as initial-order approximations of required concentrations. The initial-order approximations could be written as

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

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

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

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

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

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

$\times c_n(v)\,d\,w\,d\,v\,d\,u$, $c_n(\chi) = \cos(\pi\, n\, \chi/L_\chi)$.

We determine approximations of the second-and higher-orders framework standard iteration procedure of method of averaging of function corrections[17-19]. Framework this procedure to determine the n-th-order approximation of concentrations of dopant and radiation defects we shall replace the required functions C(x,y,z,t), I(x,y,z,t), V(x,y,z,t), $_I$(x,y,z,t) and Φ_V(x,y,z,t) in the right sides of Eqs. (1), (4), (6) on the following sums $\alpha_{n\rho}+\rho_{n-1}(x,y,z,t)$, when $\alpha_{n\rho}$ are not yet known average values of the n-th-order approximation of the above concentrations. The replacement leads to the following relations for the second-order approximations of the required concentrations

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

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

$$\left.\times\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,t)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\frac{\partial C_1(x,y,z,t)}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left\{1+\xi\frac{[\alpha_{2C}+C_1(x,y,z,t)]^\gamma}{P^\gamma(x,y,z,T)}\right\}\times\right.$$

$$\left.\times D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,t)}{V^*}+\varsigma_2\frac{V^2(x,y,z,t)}{(V^*)^2}\right]\frac{\partial C_1(x,y,z,t)}{\partial z}\right) \qquad \textbf{(8)}$$

$$\frac{\partial I_2(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial y}\right]+$$

$$+\frac{\partial}{\partial z}\left[D_I(x,y,z,T)\frac{\partial I_1(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)][\alpha_{2V}+V_1(x,y,z,t)]-$$

$$-k_{I,I}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)]^2 \qquad \textbf{(9)}$$

$$\frac{\partial V_2(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial y}\right]+$$

$$+\frac{\partial}{\partial z}\left[D_V(x,y,z,T)\frac{\partial V_1(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,t)][\alpha_{2V}+V_1(x,y,z,t)]-$$

$$-k_{V,V}(x,y,z,T)[\alpha_{2V}+V_1(x,y,z,t)]^2$$

$$\frac{\partial \Phi_{I2}(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial x}\right]+k_{I,I}(x,y,z,T)I^2(x,y,z,t)+$$

$$+\frac{\partial}{\partial y}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial y}\right]+\frac{\partial}{\partial z}\left[D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,t)}{\partial z}\right]-$$

$$-k_I(x,y,z,T)I(x,y,z,t) \tag{10}$$

$$\frac{\partial \Phi_{V2}(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial x}\right]+k_{V,V}(x,y,z,T)V^2(x,y,z,t)+$$

$$+\frac{\partial}{\partial y}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial y}\right]+\frac{\partial}{\partial z}\left[D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,t)}{\partial z}\right]-$$

$$-k_V(x,y,z,T)V(x,y,z,t).$$

Integration of left and right sides of Eqs. (8)-(10) on time gives us possibility to obtain relations for the second-order approximations of the required concentrations in the final form

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

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

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

$$\left.\times D_L(x,y,z,T)\left[1+\varsigma_1\frac{V(x,y,z,\tau)}{V^*}+\varsigma_2\frac{V^2(x,y,z,\tau)}{(V^*)^2}\right]d\tau\right)+f_C(x,y,z) \tag{8a}$$

$$I_2(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial y}d\tau\right]+$$

$$+\frac{\partial}{\partial z}\left[\int_0^t D_I(x,y,z,T)\frac{\partial I_1(x,y,z,\tau)}{\partial z}d\tau\right]-\int_0^t k_{I,I}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)]^2d\tau-$$

$$-\int_0^t k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)][\alpha_{2V}+V_1(x,y,z,\tau)]d\tau+f_I(x,y,z) \tag{9a}$$

$$V_2(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial x}d\tau\right]+\frac{\partial}{\partial y}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial y}d\tau\right]+$$

$$+\frac{\partial}{\partial z}\left[\int_0^t D_V(x,y,z,T)\frac{\partial V_1(x,y,z,\tau)}{\partial z}d\tau\right]-\int_0^t k_{V,V}(x,y,z,T)[\alpha_{2I}+V_1(x,y,z,\tau)]^2d\tau-$$

$$-\int_0^t k_{I,V}(x,y,z,T)[\alpha_{2I}+I_1(x,y,z,\tau)][\alpha_{2V}+V_1(x,y,z,\tau)]d\tau+f_V(x,y,z)$$

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$$\Phi_{I2}(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial x}d\tau\right]-\int_0^t k_I(x,y,z,T)I(x,y,z,\tau)d\tau+$$

$$+\frac{\partial}{\partial y}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial y}d\tau\right]+\frac{\partial}{\partial z}\left[\int_0^t D_{\Phi I}(x,y,z,T)\frac{\partial \Phi_{I1}(x,y,z,\tau)}{\partial z}d\tau\right]+$$

$$+\int_0^t k_{I,I}(x,y,z,T)I^2(x,y,z,\tau)d\tau+f_{\Phi I}(x,y,z) \tag{10a}$$

$$\Phi_{V2}(x,y,z,t)=\frac{\partial}{\partial x}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial x}d\tau\right]-\int_0^t k_V(x,y,z,T)V(x,y,z,\tau)d\tau+$$

$$+\frac{\partial}{\partial y}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial y}d\tau\right]+\frac{\partial}{\partial z}\left[\int_0^t D_{\Phi V}(x,y,z,T)\frac{\partial \Phi_{V1}(x,y,z,\tau)}{\partial z}d\tau\right]+$$

$$+\int_0^t k_{V,V}(x,y,z,T)V^2(x,y,z,\tau)d\tau+f_{\Phi V}(x,y,z).$$

We determine average values of the second-orders approximations of the required functions by the standard relation[17-19]

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

Substitution of the relations (8a)-(10a) into the relation (11) gives us possibility to obtain relations for the required average values $\alpha_{2\rho}$

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

$$\alpha_{2I}=\frac{1}{2A_{II00}}\left\{(1+A_{IV01}+A_{II10}+\alpha_{2V}A_{IV00})^2-4A_{II00}\left[\alpha_{2V}A_{IV10}-A_{II20}+A_{IV11}-\right.\right.$$

$$\left.\left.-\frac{1}{L_x L_y L_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z} f_I(x,y,z)\,d z\,d y\,d x\right]\right\}^{\frac{1}{2}}-\frac{1+A_{IV01}+A_{II10}+\alpha_{2V}A_{IV00}}{2A_{II00}}, \tag{13}$$

$$\alpha_{2V}=\frac{1}{2B_4}\sqrt{\frac{(B_3+A)^2}{4}-4B_4\left(y+\frac{B_3 y-B_1}{A}\right)}-\frac{B_3+A}{4B_4}.$$

Parameters A_{abij} and other parameters in the relations (13) are presented in the Appendix. Parameters α_{abij} and other parameters in the relations (13) could be written as

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$$A_{abij}=\frac{1}{\Theta L_x L_y L_z}\int_0^{\Theta}(\Theta-t)\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}k_{a,b}(x,y,z,T)I_1^i(x,y,z,t)V_1^j(x,y,z,t)\,d\,z\,d\,y\,d\,x\,d\,t,$$

$$B_4=A_{IV00}^2A_{IV00}^2-2\left(A_{IV00}^2-A_{II00}A_{VV00}\right)^2,\ B_3=A_{IV00}A_{IV00}^2+A_{IV01}A_{IV00}^3+A_{IV00}A_{II10}A_{IV00}^2-$$
$$-4\left(A_{IV00}^2-A_{II00}A_{VV00}\right)\left[2A_{IV01}A_{IV00}+2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)\right]-$$
$$-4A_{IV10}A_{IV10}A_{II00}A_{IV00}^2+2A_{IV00}A_{IV01}A_{IV00}^2,\ B_2=A_{IV00}^2\left\{\left(1+A_{IV01}+A_{II10}\right)^2+A_{IV00}^2A_{IV01}^2-A_{II00}\times\right.$$
$$\times 4\left[A_{IV11}-A_{II20}-\frac{1}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x\right]+2A_{IV00}A_{IV01}\left(A_{IV00}+A_{IV00}A_{IV01}+\right.$$
$$\left.+A_{IV00}A_{II10}-4A_{IV10}A_{II00}\right)\Big\}\Big\{\left[2A_{IV01}A_{IV00}+2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+\right.\right.$$
$$\left.+1)\right]^2+2\left[A_{IV01}\left(1+A_{IV01}+A_{II10}\right)+\frac{2}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_V(x,y,z)\,d\,z\,d\,y\,d\,x-2\left(A_{VV20}-A_{IV11}\right)\times\right.$$
$$\left.\times A_{II00}+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\right]\left[2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)+\right.$$
$$\left.+2A_{IV01}A_{IV00}\right]\Big\},\ B_1=2A_{IV00}A_{IV01}\left(1+A_{IV01}+A_{II10}\right)^2-8A_{IV00}A_{IV01}A_{II00}\left[A_{IV11}-A_{II20}-\right.$$
$$\left.-\frac{1}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x\right]+\left(A_{IV00}+A_{IV00}A_{IV01}+A_{IV00}A_{II10}-4A_{IV10}A_{II00}\right)\times$$
$$\times A_{IV01}^2-2\left[\frac{2A_{II00}}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)-\left(A_{VV20}-A_{IV11}\right)\times\right.$$
$$\left.\times 2A_{II00}+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\right]\left[2A_{IV00}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{IV10}+A_{VV10}+1\right)+\right.$$
$$\left.+2A_{IV01}A_{IV00}\right],\ B_0=4A_{II00}A_{IV01}^2\left[A_{II20}+\frac{1}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_I(x,y,z)\,d\,z\,d\,y\,d\,x-A_{IV11}\right]-$$
$$-\left[\frac{2A_{II00}}{L_xL_yL_z}\int_0^{L_x}\int_0^{L_y}\int_0^{L_z}f_V(x,y,z)\,d\,z\,d\,y\,d\,x+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)-2A_{II00}\left(A_{VV20}-A_{IV11}\right)+\right.$$
$$\left.+A_{IV01}\left(1+A_{IV01}+A_{II10}\right)\right]^2+A_{IV01}^2\left(A_{IV01}+A_{II10}+1\right)^2,\ y=\sqrt[3]{\sqrt{q^2+p^3}-q}+B_2/6-$$
$$-\sqrt[3]{\sqrt{q^2+p^3}+q},\ q=\frac{1}{8}\left[\frac{B_2^3}{27}+B_0\left(4B_2-B_3^2\right)-B_1^2+\frac{B_2}{6}\left(2B_1B_3-8B_0\right)\right],\ A=\sqrt{8y+B_3^2-4B_2},$$
$$p=\left[3\left(2B_1B_3-8B_0\right)-2B_2^2\right]/72.$$

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$$\alpha_{2\Phi_I} = A_{II20} - \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta} (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} k_I(x,y,z,T) I(x,y,z,t) d\,z\,d\,y\,d\,x\,d\,t +$$

$$+ \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_{\Phi I}(x,y,z) d\,z\,d\,y\,d\,x \tag{14}$$

$$\alpha_{2\Phi_V} = A_{VV20} - \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta} (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} k_V(x,y,z,T) V(x,y,z,t) d\,z\,d\,y\,d\,x\,d\,t +$$

$$+ \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_{\Phi V}(x,y,z) d\,z\,d\,y\,d\,x .$$

The considered substitution gives us possibility to obtain equation for parameter α_{2C}. Solution of the equation depends on value of parameter γ. Analysis of spatio- temporal distributions of concentrations of dopant and radiation defects has been done by using their second-order approximations framework method of averaging of function corrections with decreased quantity of iterative steps. The second-order approximation is usually a sufficient approximation to obtain qualitative and some quantitative results. Results of analytical modeling have been checked numerically.

DISCUSSION

Based on recently calculated relations we analyzed redistribution of dopant and radiation defects. Figures 2a and 2b show distributions of concentrations of infused (Figure 2a) and implanted (Figure 2b) dopants in channels and in nearest areas. These distributions had been calculated for the case, when value of dopant diffusion coefficient in doped materials is larger, than value of dopant diffusion coefficient in

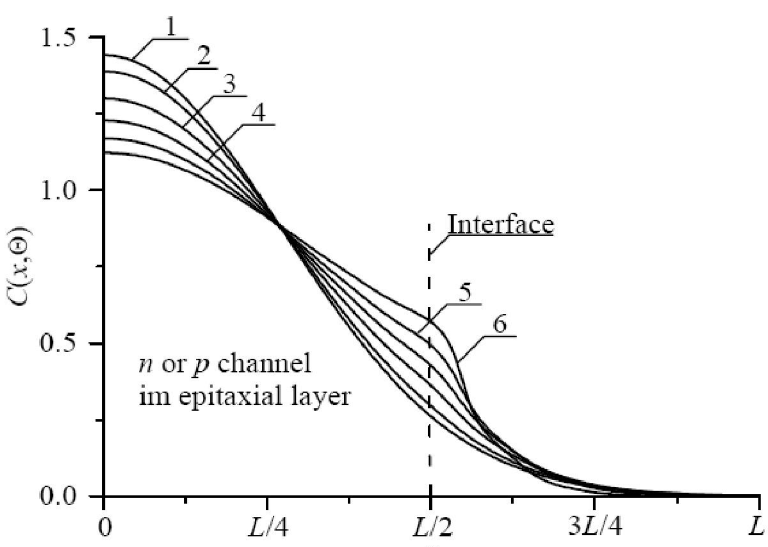

Figure 2a : Distributions of concentrations of infused dopant in heterostructure from Figure 1 in direction, which is perpendicular to interface between layers of heterostructure. Increasing of number of curves corresponds to increasing of difference between values of dopant diffusion coefficient in layers of heterostructure. The curves have been calculated under condition, when dopant diffusion coefficient in doped layer is larger, than in nearest layer

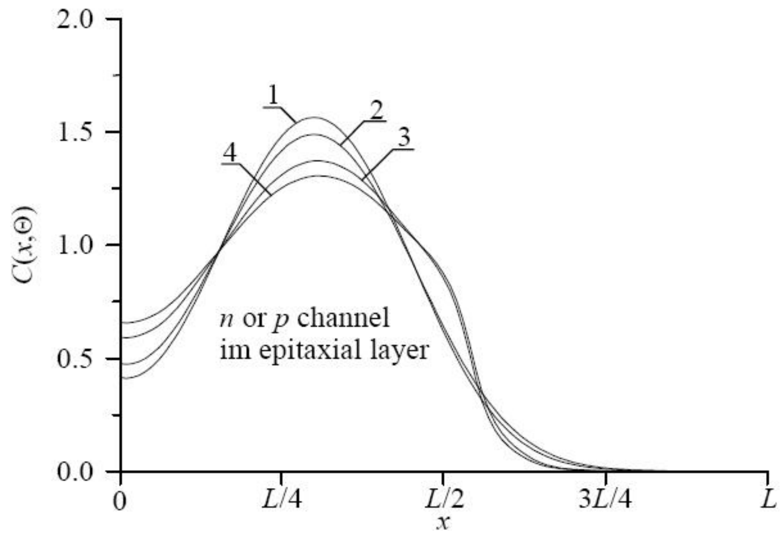

Figure 2b : Spatial distributions of implanted dopant concentration after annealing. Cur-ves 1 and 2 are calculated distributions of dopant concentration in homogenous structure for two values of annealing time ($\Theta = 0{,}0048(L_x^2+L_y^2+L_z^2)/D_0$ and $\Theta = 0{,}0057(L_x^2+L_y^2+L_z^2)/D_0$, respectively). Curves 3 and 4 are calculated distributions of dopant concentration in heterostructure for the same values of annealing time under condition, when dopant diffusion coefficient in doped layer is larger, than in nearest layer

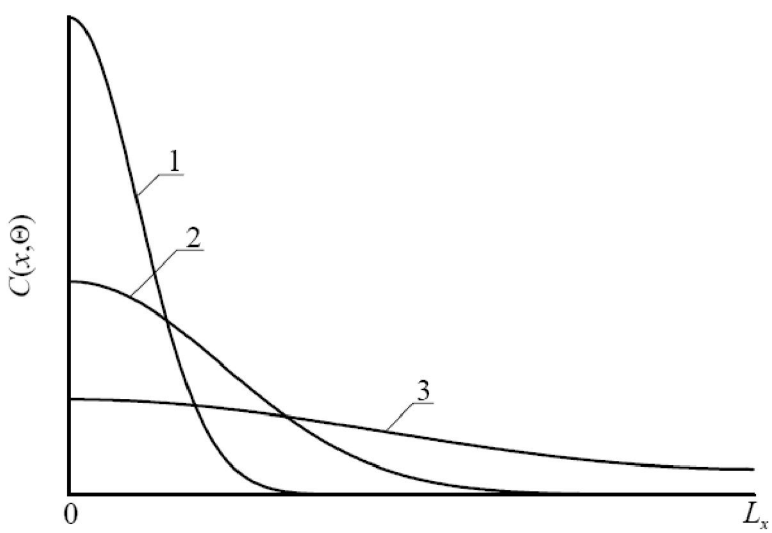

Figure 3a : Spatial distributions of concentration of implanted dopant in heterostructure from Figures 1. Curves 1-3 are distributions of dopant for different values of annealing time. Increasing of number of curve corresponds to increasing of annealing time

nearest areas. In this case it is possible to increase density of channels in transistors and, as a consequence, to decrease dimensions of multi-channel transistor. At the same time the considered approach of doping gives us possibility to increase homogeneity of concentrations of dopants in channels of the considered transistors. The effect gives us possibility to increase density of current in the channels at fixed value of maximal heating of the doped material or to decrease length of channels. It should be noted, that using ion implantation gives us possibility to increase homogeneity of concentrations of dopants in channels and at the same time to decrease their quantities in nearest materials due to radiation-induced diffusion.

Analysis of changing of concentration of dopant in time shown necessity of optimization of annealing time. Reason of the optimization is too large diffusion depth of dopants from channels of transistors into nearest materials. Figures 3 are illustrations of this situations. We determine optimal value of annealing time framework recently introduced criterion[10,11,19-25]. Framework the criterion we approximate real dis-

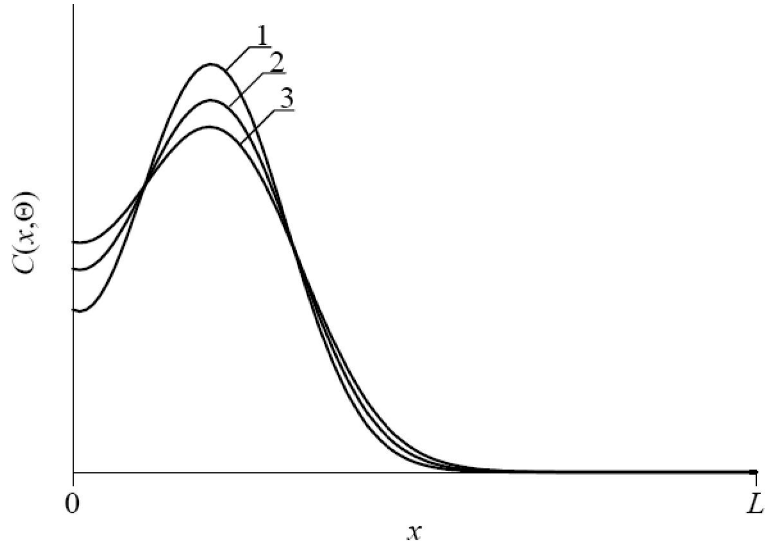

Figure 3b : Spatial distributions of concentration of infused dopant in heterostructure from Figures 1. Curves 1-3 are the real distributions of dopant for different values of annealing time. Increasing of number of curve corresponds to increasing of annealing time

tribution of concentration of dopant by idealized step-wise function ψ (x,y,z). Farther we determine optimal value of annealing time by minimization of the following mean- squared error

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

Distributions of concentrations of dopants in Figures 2 corresponds exactly to compromise annealing time.

CONCLUSIONS

In this paper we introduce an approach for manufacturing a multi-channel heterotransistor. Several recommendations to optimize technological process for decreasing dimensions of transistor.

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