AN APPROACH TO MODEL OPTIMIZATION OF MANUFACTURING OF EMITTER-COUPLED LOGIC

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ABSTRACT

In this paper we consider an approach to optimize manufacturing elements of emitter-coupled logic. The optimization leads to decreasing dimensions of these elements. Framework this paper we consider manufacturing these elements of emitter-coupled logic framework a heterostructure with required configuration. After grown the heterostructure the required areas have been doped by diffusion or ion implantation. It is attracted an interest optimization of annealing of dopant and/or radiation defects to decrease dimensions of the considered elements. We consider an approach to make the optimization. The modeling part based on modified method of functional corrections, which gives us possibility to analyzed manufacturing the elements of emitter-coupled logic without crosslinking of solutions on interfaces between layers of heterostructure.

KEYWORDS

analytical approach for modelling; emitter-coupled logic; optimization of manufacturing; decreasing of dimensions; decreasing of overheats

1. INTRODUCTION

Intensive development of electronic technique leads to increasing of performance of elements of integrated circuits ant to increasing of degree of their integration (*p*-*n*-junctions, bipolar and field-effect transistors, thyristors, ...) [1-6]. Increasing of the performance could be obtain by development of new and optimization of existing technological processes. Another way to increase the performance in determination of materials with higher speed of transport of charge carriers [7-10]. At the same time with increasing of degree of integration rate of elements of integrated circuits dimensions of their elements decreased. To decrease the dimensions it could be used different approaches. Two of them (laser and microwave types of annealing) based on generation of inhomogenous distribution of temperature [11-13]. The inhomogeneity gives us possibility to decrease dimensions of elements of integrated circuits due to Arrhenius law. Another way to decrease the dimensions is doping of epitaxial layers of heterostructures by diffusion and ion implantation [14-17]. However this type of doping leads to necessity to optimize annealing of dopant and/or radiation defects [17-24]. Distributions of concentrations of dopants in heterostructures and homogeneous samples could be changed not only by heating and cooling, but radiation processing too [25].

In this paper as a development of works [17-24] we consider an approach to manufacture more compact elements of emitter-coupled logic. To illustrate the approach we consider a heterostructure, which is illustrated on Fig. 1. The heterostructure consist of a substrate and three epitaxial layers. Some sections have been manufactured in the epitaxial layers such as it shown on the fig-

ure. After finishing of the nearest to the substrate epitaxial layer we consider doping of the sections of the layer by diffusion or ion implantation. The sections will have role of collectors during functioning of the manufacturing device. Farther dopant and/or radiation defects should be annealed. After finishing this annealing we consider two another epitaxial layers with appropriate sections (see Fig. 1). All sections of the last layers have been also doped by diffusion or ion implantation. In our situation it is attracted an interest microwave annealing of dopant and/or radiation defects. Frequency of electro-magnetic radiation should be so, that thickness of scin-layer should be larger, than thickness of external epitaxial layer and smaller, than sum of thicknesses of external and average epitaxial layers. Sections of the average and external epitaxial layers will have roles of bases and emitter, respectively, during functioning of the considered device. In the present paper we analyzed of dynamics of redistribution of infused and implanted dopants and/or radiation defects during annealing.

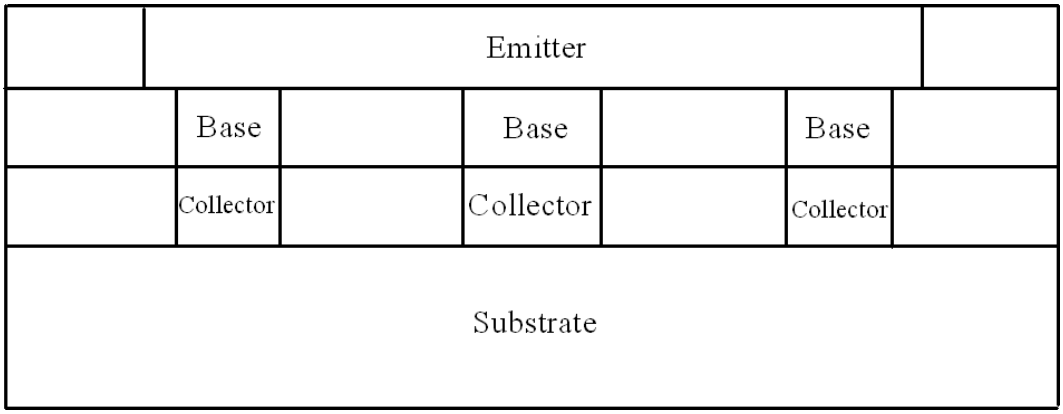

Fig. 1. Heterostructure with four layers, which consist of a substrate and three epitaxial layer with sections, manufactured by using another materials

2. METHOD OF SOLUTION

We determine spatio-temporal distribution of concentration of dopant to solve our aims. We determine the required distribution by solving the second Fick's law [1,14-17]

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

with initial and boundary conditions

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

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

The function $C(x,y,z,t)$ described the spatio-temporal distribution of concentration of dopant in the Eq.(1) and appropriate boundary and initial conditions; argument of the considered function described current coordinates and current time; T is the temperature of annealing; D_C is the dopant diffusion coefficient. Value of dopant diffusion coefficient is different in different materials

and varying with heating and cooling of the heterostructure (with account Arrhenius law). Dopant diffusion coefficient as a function of parameters could be approximated by the following relation [26-28]

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

Function $D_L(x,y,z,T)$ in the Eq.(3) describes spatial and temperature dependences of dopant diffusion coefficient. Spatial dependence of dopant diffusion coefficient is occur due to presents several layers with different properties framework heterostructure. Temperature dependence of dopant diffusion coefficient is occur due to Arrhenius law. Function $P(x,y,z,T)$ describes dependence limit of solubility of dopant on spatial coordinates and temperature. Parameter γ has different values in different materials and could be integer in the following interval $\gamma\in[1,3]$ [26]. Function $V(x,y,z,t)$ describes the spatio-temporal distribution of radiation vacancies; V^* is the equilibrium distribution of vacancies. We used concentrational dependence of dopant diffusion coefficient from [26]. It should be noted, that diffusion type of doping did not leads to generation of radiation defects. In this situation $\zeta_1=\zeta_2=0$. Spatio-temporal distributions of concentrations of point radiation defects (interstitials and vacancies) have been determined by solution of the following system of equations [27,28]

$$\begin{cases}
\dfrac{\partial I(x,y,z,t)}{\partial t}=\dfrac{\partial}{\partial x}\left[D_I(x,y,z,T)\dfrac{\partial I(x,y,z,t)}{\partial x}\right]+\dfrac{\partial}{\partial y}\left[D_I(x,y,z,T)\dfrac{\partial I(x,y,z,t)}{\partial y}\right]+ \\
+\dfrac{\partial}{\partial z}\left[D_I(x,y,z,T)\dfrac{\partial I(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)\,I(x,y,z,t)V(x,y,z,t)- \\
-k_{I,I}(x,y,z,T)\,I^2(x,y,z,t) \\
\dfrac{\partial V(x,y,z,t)}{\partial t}=\dfrac{\partial}{\partial x}\left[D_V(x,y,z,T)\dfrac{\partial V(x,y,z,t)}{\partial x}\right]+\dfrac{\partial}{\partial y}\left[D_V(x,y,z,T)\dfrac{\partial V(x,y,z,t)}{\partial y}\right]+ \\
+\dfrac{\partial}{\partial z}\left[D_V(x,y,z,T)\dfrac{\partial V(x,y,z,t)}{\partial z}\right]-k_{I,V}(x,y,z,T)\,I(x,y,z,t)V(x,y,z,t)- \\
-k_{V,V}(x,y,z,T)\,V^2(x,y,z,t)
\end{cases} \qquad (3)$$

Boundary and initial conditions for the equations are

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

$$I(x,y,z,0)=f_I(x,y,z),\ V(x,y,z,0)=f_V(x,y,z). \qquad (4)$$

Here $\rho=I,V$; spatio-temporal distribution of concentration of radiation interstitials has been described by the following function $I(x,y,z,t)$; diffusion coefficients of interstitials and vacancies are

$D_\rho(x,y,z,T)$; square terms $V^2(x,y,z,t)$ and $I^2(x,y,z,t)$ give a possibility to take into account generation diinterstitials and divacancies; functions $k_{\rho,\rho}(x,y,z,T)$ and $k_{I,V}(x,y,z,T)$ describe spatio-temperature distribution of parameters of generation complexes of point radiation defects and recombination. Spatio-temporal distributions of concentrations of simplest complexes (divacancies $\Phi_V(x,y,z,t)$ and diinterstitials $\Phi_I(x,y,z,t)$) of radiation defects have been described as solution of the following system of equations [27,28]

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

Initial and boundary conditions for the equations are

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

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

Spatio-temporal distribution of temperature has been determine as solution of the second law of Fourier [29]

$$c(T)\frac{\partial T(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(x,y,z,T)\frac{\partial T(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(x,y,z,T)\frac{\partial T(x,y,z,t)}{\partial y}\right] +$$
$$+ \frac{\partial}{\partial z}\left[\lambda(x,y,z,T)\frac{\partial T(x,y,z,t)}{\partial z}\right] + p(x,y,z,t). \quad (8)$$

Initial and boundary conditions for the equation are

$$\left.\frac{\partial T(x,y,z,t)}{\partial x}\right|_{x=0} = 0,\ \left.\frac{\partial T(x,y,z,t)}{\partial x}\right|_{x=L_x} = 0,\ \left.\frac{\partial T(x,y,z,t)}{\partial y}\right|_{y=0} = 0,\ \left.\frac{\partial T(x,y,z,t)}{\partial y}\right|_{x=L_y} = 0,$$
$$\left.\frac{\partial T(x,y,z,t)}{\partial z}\right|_{z=0} = 0,\ \left.\frac{\partial T(x,y,z,t)}{\partial z}\right|_{x=L_z} = 0,\ T(x,y,z,0)=f_T(x,y,z). \quad (9)$$

The function $T(x,y,z,t)$ describes the spatio-temporal distribution of temperature of annealing; $c(T)= c_{ass}[1-\eta\ exp(-T(x,y,z,t)/T_d)]$ is the heat capacitance (in the most interest case, when current

temperature is approximately equal or larger, than Debye temperature T_d, we have possibility to consider the following limiting case $c\ (T)\approx c_{ass}$) [29]; λ is the heat conduction coefficient, which depends on properties of materials and temperature (dependence on temperature of the heat conduction coefficient could be approximated by the function $\lambda(x,y,z,T)=\lambda_{ass}(x,y,z)[1+\mu (T_d/T(x,y,z,t))^{\varphi}]$ in the most interesting interval of temperature [29]); $p(x,y,z,t)$ is the volumetric density of power of heating; $\alpha(x,y,z,T)=\lambda(x, y,z,T)/c\ (T)$ is the thermal diffusivity.

With account temperature dependence of parameters spatio-temporal distribution of temperature should be calculated first-ever. To make the calculation we used recently considered approach [17,20,30]. Framework the approach we transform approximation of thermal diffusivity to the following form: $\alpha_{ass}(x,y,z)=\lambda_{ass}(x,y,z)/c_{ass}=\alpha_{0ass}[1+\varepsilon_T g_T(x,y,z)]$. Farther we determine solution of the Eq.(8) as the following power series [17,20,30]

$$T(x,y,z,t)=\sum_{i=0}^{\infty}\varepsilon_T^i\sum_{j=0}^{\infty}\mu^j T_{ij}(x,y,z,t). \qquad (10)$$

System of equations for determination $T_{ij}(x,y,z,t)$ ($i\geq 0$, $j\geq 0$) have been obtained by substitution the series into Eq.(8). Boundary and initial conditions have been obtained by the same procedure. The procedure is standard and will not be present in this paper. Solutions of the equations for the functions $T_{ij}(x,y,z,t)$ ($i\geq 0$, $j\geq 0$) have been calculated by standard Fourier approache [31, 32] framework the second-order approximation on parameters ε and μ. The second-order approximation is usually enough good approximation to make qualitative analysis and to obtain some quantitative results (see, for example, [17,20,30]). Analytical results leads to more demonstrable analysis of described process. The obtained analytical results have been checked by comparison with numerical one.

Spatio-temporal distributions of concentrations of point defects have been calculated by recently introduces approach [17,20,30]. Framework the approach we transform approximation of their diffusion coefficients to the following form $D_{\rho}(x,y,z,T)=D_{0\rho}[1+\varepsilon_{\rho}g_{\rho}(x,y,z,T)]$, where $D_{0\rho}$ are the average values of the diffusion coefficients, $0\leq\varepsilon_{\rho}<1$, $|g_{\rho}(x,y,z,T)|\leq 1$, $\rho=I,V$. Analogous transformation of approximations of parameters of recombination of point defects and generation their complexes has been used: $k_{I,V}(x,y,z,T)=k_{0I,V}[1+\varepsilon_{I,V}g_{I,V}(x,y,z,T)]$, $k_{I,I}(x,y,z,T)=k_{0I,I}[1+\varepsilon_{I,I}g_{I,I}(x,y,z,T)]$ and $k_{V,V}(x,y,z,T)=k_{0V,V}[1+\varepsilon_{V,V}g_{V,V}(x,y,z,T)]$, where $k_{0\rho1,\rho2}$ are the appropriate average values, $0\leq\varepsilon_{I,V}<1$, $0\leq\varepsilon_{I,I}<1$, $0\leq\varepsilon_{V,V}<1$, $|g_{I,V}(x,y,z,T)|\leq 1$, $|g_{I,I}(x,y,z,T)|\leq 1$, $|g_{V,V}(x,y,z,T)|\leq 1$. Let us introduce following dimensionless variables: $\tilde{I}(x,y,z,t)=I(x,y,z,t)/I^*$, $\tilde{V}(x,y,z,t)=V(x,y,z,t)/V^*$, $\chi=x/L_x$, $\eta=y/L_y$, $\phi=z/L_z$, $\vartheta=\sqrt{D_{0I}D_{0V}}\,t/L^2$, $\omega=L^2k_{0I,V}/\sqrt{D_{0I}D_{0V}}$, $\Omega_{\rho}=L^2k_{0\rho,\rho}/\sqrt{D_{0I}D_{0V}}$. The introduction leads to following transformation of Eqs.(4) and conditions (5)

$$\frac{\partial\tilde{I}(\chi,\eta,\phi,\vartheta)}{\partial\vartheta}=\frac{D_{0I}}{\sqrt{D_{0I}D_{0V}}}\frac{\partial}{\partial\chi}\left\{[1+\varepsilon_I g_I(\chi,\eta,\phi,T)]\frac{\partial\tilde{I}(\chi,\eta,\phi,\vartheta)}{\partial\chi}\right\}+\frac{D_{0I}}{\sqrt{D_{0I}D_{0V}}}\times$$
$$\times\frac{\partial}{\partial\eta}\left\{[1+\varepsilon_I g_I(\chi,\eta,\phi,T)]\frac{\partial\tilde{I}(\chi,\eta,\phi,\vartheta)}{\partial\eta}\right\}+\frac{D_{0I}}{\sqrt{D_{0I}D_{0V}}}\frac{\partial}{\partial\phi}\left\{[1+\varepsilon_I g_I(\chi,\eta,\phi,T)]\frac{\partial\tilde{I}(\chi,\eta,\phi,\vartheta)}{\partial\phi}\right\}-$$
$$-\omega\,[1+\varepsilon_{I,V}g_{I,V}(\chi,\eta,\phi,T)]\tilde{I}(\chi,\eta,\phi,\vartheta)\tilde{V}(\chi,\eta,\phi,\vartheta)-\Omega_I\,\tilde{I}^2(\chi,\eta,\phi,\vartheta)[1+\varepsilon_{I,I}g_{I,I}(\chi,\eta,\phi,T)] \qquad (11)$$
$$\frac{\partial\tilde{V}(\chi,\eta,\phi,\vartheta)}{\partial\vartheta}=\frac{D_{0V}}{\sqrt{D_{0I}D_{0V}}}\frac{\partial}{\partial\chi}\left\{[1+\varepsilon_V g_V(\chi,\eta,\phi,T)]\frac{\partial\tilde{V}(\chi,\eta,\phi,\vartheta)}{\partial\chi}\right\}+\frac{D_{0V}}{\sqrt{D_{0I}D_{0V}}}\times$$

$$\times \frac{\partial}{\partial \eta}\left\{\left[1+\varepsilon_V g_V(\chi,\eta,\phi,T)\right]\frac{\partial \tilde{V}(\chi,\eta,\phi,\vartheta)}{\partial \eta}\right\}+\frac{\partial}{\partial \phi}\left\{\left[1+\varepsilon_V g_V(\chi,\eta,\phi,T)\right]\frac{\partial \tilde{V}(\chi,\eta,\phi,\vartheta)}{\partial \phi}\right\}\frac{D_{0V}}{\sqrt{D_{0I}D_{0V}}}-$$

$$-\omega\left[1+\varepsilon_{I,V} g_{I,V}(\chi,\eta,\phi,T)\right]\tilde{I}(\chi,\eta,\phi,\vartheta)\tilde{V}(\chi,\eta,\phi,\vartheta)-\Omega_V \tilde{V}^2(\chi,\eta,\phi,\vartheta)\left[1+\varepsilon_{V,V} g_{V,V}(\chi,\eta,\phi,T)\right]$$

$$\left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \chi}\right|_{\chi=0}=0,\ \left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \chi}\right|_{\chi=1}=0,\ \left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \eta}\right|_{\eta=0}=0,\ \left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \eta}\right|_{\eta=1}=0,$$

$$\left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \phi}\right|_{\phi=0}=0,\ \left.\frac{\partial \tilde{\rho}(\chi,\eta,\phi,\vartheta)}{\partial \phi}\right|_{\phi=1}=0,\ \tilde{\rho}(\chi,\eta,\phi,\vartheta)=\frac{f_\rho(\chi,\eta,\phi,\vartheta)}{\rho^*}. \qquad (12)$$

We solved the Eqs.(11) with conditions (12) by using the approach, considered in [17,20,30]. Framework the approach we determine solutions of the equations as the following power series

$$\tilde{\rho}(\chi,\eta,\phi,\vartheta)=\sum_{i=0}^{\infty}\varepsilon_\rho^i\sum_{j=0}^{\infty}\omega^j\sum_{k=0}^{\infty}\Omega_\rho^k\tilde{\rho}_{ijk}(\chi,\eta,\phi,\vartheta). \qquad (13)$$

Equations for the functions $\tilde{\rho}_{ijk}(\chi,\eta,\phi,\vartheta)$ ($i\geq 0$, $j\geq 0$, $k\geq 0$) could be obtained by substitution of the series (13) into Eqs.(11). Initial and boundary conditions could be obtained by substitution of the series (13) into conditions (12). Equations for the functions $\tilde{\rho}_{ijk}(\chi,\eta,\phi,\vartheta)$ with appropriate initial and boundary conditions have been solved by standard Fourier approach [31,32].

Now we shall solve system of equations (6) to calculate spatio-temporal distributions of concentrations of complexes of radiation defects. To determine these distributions we transform approximations of diffusion coefficients to the following form: $D_{\Phi\rho}(x,y,z,T)=D_{0\Phi\rho}[1+\varepsilon_{\Phi\rho}g_{\Phi\rho}(x,y,z,T)]$, where $D_{0\Phi\rho}$ are the average values of the coefficients. In this situation the Eqs. (6) have been transform to the following form

$$\frac{\partial \Phi_I(x,y,z,t)}{\partial t}=D_{0\Phi_I}\frac{\partial}{\partial x}\left\{\left[1+\varepsilon_{\Phi_I}g_{\Phi_I}(x,y,z,T)\right]\frac{\partial \Phi_I(x,y,z,t)}{\partial x}\right\}+D_{0\Phi_I}\times$$

$$\times\frac{\partial}{\partial y}\left\{\left[1+\varepsilon_{\Phi_I}g_{\Phi_I}(x,y,z,T)\right]\frac{\partial \Phi_I(x,y,z,t)}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{\left[1+\varepsilon_{\Phi_I}g_{\Phi_I}(x,y,z,T)\right]\frac{\partial \Phi_I(x,y,z,t)}{\partial z}\right\}\times$$

$$\times D_{0\Phi_I}+k_{I,I}(x,y,z,T)I^2(x,y,z,t)-k_I(x,y,z,T)I(x,y,z,t)$$

$$\frac{\partial \Phi_V(x,y,z,t)}{\partial t}=D_{0\Phi_V}\frac{\partial}{\partial x}\left\{\left[1+\varepsilon_{0\Phi_V}g_{0\Phi_V}(x,y,z,T)\right]\frac{\partial \Phi_V(x,y,z,t)}{\partial x}\right\}+D_{0\Phi_V}\times$$

$$\times\frac{\partial}{\partial y}\left\{\left[1+\varepsilon_{\Phi_V}g_{\Phi_V}(x,y,z,T)\right]\frac{\partial \Phi_V(x,y,z,t)}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{\left[1+\varepsilon_{\Phi_V}g_{\Phi_V}(x,y,z,T)\right]\frac{\partial \Phi_V(x,y,z,t)}{\partial z}\right\}\times$$

$$\times D_{0\Phi_V}+k_{V,V}(x,y,z,T)V^2(x,y,z,t)-k_V(x,y,z,T)V(x,y,z,t).$$

We determine solutions of the equations as the power series

$$\Phi_\rho(x,y,z,t)=\sum_{i=0}^{\infty}\varepsilon_{\Phi\rho}^i\Phi_{\rho i}(x,y,z,t). \qquad (14)$$

Equations for the functions $\Phi_{\rho i}(x,y,z,t)$ ($i \geq 0$), initial and boundary conditions could be obtain by substitution of the series (14) into Eqs.(6) and conditions (7). The equation have been solved by standard Fourier approach [31,32].

To calculate spatio-temporal distribution of concentration of dopant we used recently introduced approach [17,20]. Framework the approach we transform approximation of dopant diffusion coefficient in the following form: $D_L(x,y,z,T)=D_{0L}[1+\varepsilon_L g_L(x,y,z,T)]$. Here D_{0L} is the average value of dopant diffusion coefficient. Function $g_L(x,y,z,T)$ and parameter ε_L have the following limitation $|g_L(x,y,z,T)| \leq 1$, $0 \leq \varepsilon_L < 1$. Farther we determine solution of Eq.(1) as the following power series

$$C(x,y,z,t) = \sum_{i=0}^{\infty} \varepsilon_L^i \sum_{j=1}^{\infty} \xi^j C_{ij}(x,y,z,t). \qquad (15)$$

Equations for functions $C_{ij}(x,y,z,t)$ ($i \geq 0$, $j \geq 0$), initial and boundary conditions could be obtained by substitution of the series in the Eq.(1) and condition (2). The equations have been solved by standard Fourier approach [31,32].

We analyzed spatiotemporal distributions of temperature, concentration of dopant and concentrations radiation defects by using the second-order approximations with account all considered parameters. Recently we obtain, that the second-order approximations are usually enough good to obtain some quantitative results and make qualitative analysis [17,20,30]. Obtained analytical approaches give a possibility to analyze physical processes more demonstrably in comparison with numerical one. We check analytical results by comparison with numerical one.

3. Discussion

Let us analyzed dynamic of redistribution of dopant and radiation defects in the considered heterostructure during their annealing. We analyzed the dynamic by using calculated in the previous section relations. Several distributions of concentrations of dopant in the considered in Fig. 1 heterostructures are presented on Figs. 2 and 3. The Fig. 2 shows distributions of concentrations of dopant for diffusion type of doping. The Fig. 3 shows distributions of concentrations of dopant for ion type of doping. The figures show distributions for lager value of dopant diffusion coefficient in doped area in comparison with nearest one. One can find from these figures, that sharpness of *p*-*n*-junctions could be increased by using inhomogeneity of heterostructure. One can find the same situation in doped sections of epitaxial layer. Increasing of sharpness of *p*-*n*-junctions leads to decreasing their switching time. It should be also noted, that increasing of homogeneity of distribution of dopant in doped area leads to decreasing local overheat of doped material during functioning of *p*-*n*-junction. Another way of using the increasing of homogeneity is decreasing of dimensions of the *p*-*n*-junction for fixed maximal value of local overheat. On the other hand inhomogeneity of doping of base of transistor leads to generation an electric field in the base. One can find acceleration of transport of charge carriers by he electric field. The acceleration gives us possibility to increase performance of the transistor.

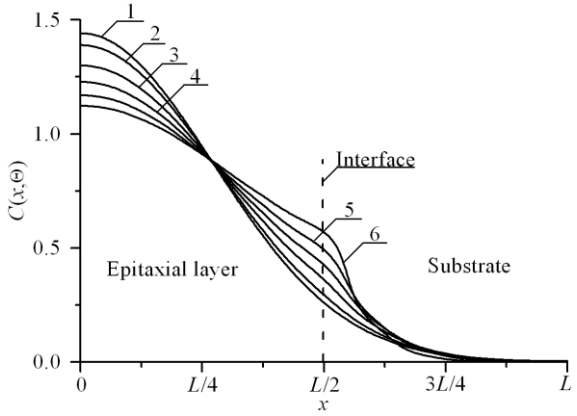

Fig.2. Distributions of concentration of dopant in the considered heterostructure for diffusion type of doping. The distributions have been calculated for direction, which is perpendicular to interface between epitaxial layer substrate. Increasing of number of curve corresponds to increasing of difference between values of dopant diffusion coefficient in layers of heterostructure

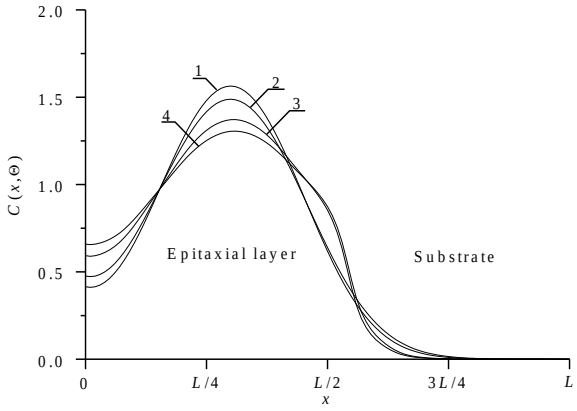

Fig.3. Distributions of concentration of dopant in the considered heterostructure for ion type of doping. The distributions have been calculated for direction, which is perpendicular to interface between epitaxial layer substrate. Curves 1 and 3 corresponds to annealing time $\Theta=0.0048(L_x^2+ L_y^2+L_z^2)/D_0$. 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 heterostructure

It is attracted an interest to use microwave annealing to improve properties of drift transistors. This type of annealing leads to generation inhomogenous distribution of temperature. The inhomogeneity leads to increase homogeneity of distribution of concentration of dopant due to Arrhenius law [33]. It is known, that one should to choose frequency of electro-magnetic irradiation so, that thickness of scin-layer should be larger, than thickness of external epitaxial layer, and smaller, than sum of thicknesses of external and average epitaxial layers.

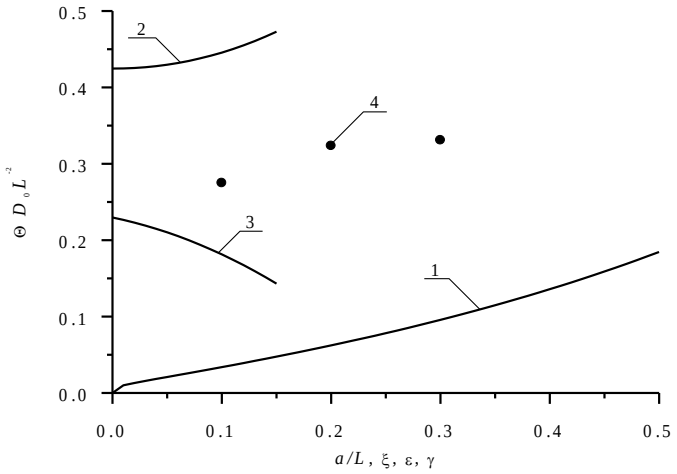

Fig.4. Dependences of dimensionless optimal annealing time of dopant for diffusion type of doping. Parameters of these curves are following: curve 1 is the dependence of dimensionless optimal annealing time on the relation a/L and $\xi=\gamma=0$ for equal to each other values of dopant diffusion coefficient in all parts of heterostructure; curve 2 is the dependence of dimensionless optimal annealing time on value of parameter ε for $a/L=1/2$ and $\xi=\gamma=0$; curve 3 is the dependence of dimensionless optimal annealing time on value of parameter ξ for $a/L=1/2$ and $\varepsilon=\gamma=0$; curve 4 is the dependence of dimensionless optimal annealing time on value of parameter γ for $a/L=1/2$ and $\varepsilon=\xi=0$

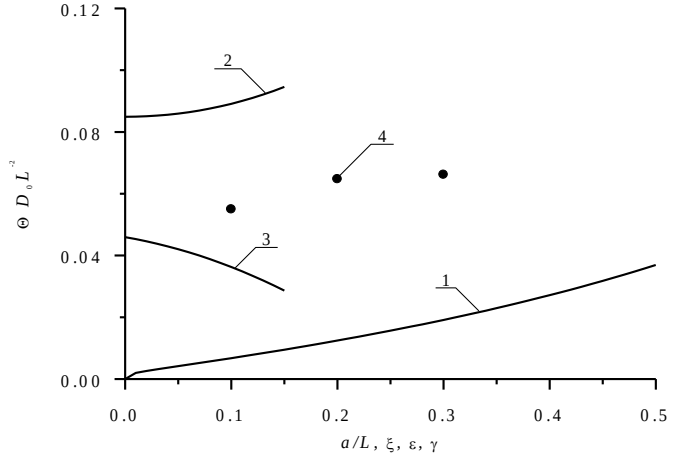

Fig.5. Dependences of dimensionless optimal annealing time of dopant for ion type of doping. Parameters of these curves are following: curve 1 is the dependence of dimensionless optimal annealing time on the relation a/L and $\xi=\gamma=0$ for equal to each other values of dopant diffusion coefficient in all parts of heterostructure; curve 2 is the dependence of dimensionless optimal annealing time on value of parameter ε for $a/L=1/2$ and $\xi=\gamma=0$; curve 3 is the dependence of dimensionless optimal annealing time on value of parameter ξ for $a/L=1/2$ and $\varepsilon=\gamma=0$; curve 4 is the dependence of dimensionless optimal annealing time on value of parameter γ for $a/L=1/2$ and $\varepsilon=\xi=0$

It is known, that increasing of annealing time give a possibility to increase homogeneity of distribution of concentration of dopant. In this situation the distribution became too large. If annealing time is too small, dopant has not time to achieve nearest interface between materials of heterostructure. In this situation distribution of concentration of dopant has not any changing. In this situation it is attracted an interest optimization of annealing. We consider the optimization of annealing framework recently introduced criterion [17-24,33]. To use the criterion we shall approx-

imate real distributions of concentrations of dopants by step-wise function $\psi(x,y,z)$. Farther we minimize the following mean-squared error to optimize annealing time

$$U = \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} \left[C(x, y, z, \Theta) - \psi(x, y, z) \right] dz\, dy\, dx . \quad (16)$$

We illustrate dependences of optimal values of annealing time by Figs. 4 and 5. Optimal values of annealing time of implanted dopant is smaller, than optimal values of annealing time of infused dopant. The difference existing due to necessity of annealing of radiation defects. During annealing radiation defects one can find spreading of distribution of concentration of dopant. In the ideal case during annealing of radiation defects should achieves interface between materials of heterostructure. If dopant has no time to achieve the interface, additional annealing of dopant attracted an interest. The Fig. 5 shows exactly dependences of time of additional annealing.

4. CONCLUSIONS

In this paper we consider an approach to manufacture more compact elements of emitter-coupled logic. Framework the approach one shall manufacture a heterostructure with required configuration. After that required parts of heterostructures should be doped by diffusion or ion implantation. The doping should done with optimized annealing of dopant and/or radiation defects.

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