ON OPTIMIZATION OF MANUFACTURING OF MULTI-CHANNEL HETEROTRANSISTORS TO INCREASE THEIR INTEGRATION RATE

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ABSTRACT

In this paper we consider an approach to increase integration rate of field-effect heterotransistors. Framework the approach we consider a heterostructure with specific configuration. After manufacturing the heterostructure we consider doping of required areas of the heterostructure by diffusion or ion implantation. The doping finished by 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.

KEYWORDS

Field-effect heterotransistors; multi-channel heterotransistors; increasing of integration rate

1. INTRODUCTION

In the present time integration rate of elements of integrated circuits intensively increasing [1-6]. Increasing of the integration rate leads to necessity to decrease dimensions of these elements. Are they widely using to decrease these elements laser and microwave types of annealing [7-11]. It could be also used radiation processing of doped materials to solve the same problem [12,13].

Fig. 1a. Heterostructure which includes into itself a substrate and an epitaxial layer. Side view
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In this paper we consider manufacturing a multi-channel heterotransistor with common gate. The heterotransistor has been manufactured framework a heterostructure, which include into itself a substrate and an epitaxial layer. The epitaxial layer includes into itself several sections (see Fig. 1). After manufacturing of the required quantity of channels they should be doped to generation required type of conductivity (n or p). Farther we consider annealing of dopant and/or radiation defects. 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 analysis of spatio-temporal distributions of concentrations of dopant and radiation defects and temperature to determine conditions to decrease dimension of the considered heterotransistor.

Fig. 1b. Heterostructure which includes into itself a substrate and an epitaxial layer. Top view

2. METHOD OF SOLUTION

We solved our aim by calculation of 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

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

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

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

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 will have different values in different materials. The value will be changed during heating and cooling of heterostructure (with account Arrhenius law). Approximation of dopant diffusion coefficient by the following function [13-15]

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

Function $D_L(x,y,z,T)$ describes the spatial and temperature dependences of dopant diffusion coefficient. One can find these dependences due to presents several layers in heterostructure and the Arrhenius law, respectively. Function $P(x,y,z,T)$ describes the limit of solubility of dopant. Parameter $\gamma \in [1,3]$ has different values in different materials [14]. The function $V(x,y,z,t)$ describes the spatio-temporal distribution of concentration of radiation vacancies. V^* is the equilibrium distribution of concentration of vacancies. Dependence of dopant diffusion coefficient on concentration of dopant has been described in details in [14]. It is known, that doping of materials by diffusion did not leads to generation radiation defects. In this situation $\zeta_1 = \zeta_2 = 0$. It should be also noted, that we solved more common boundary problem in comparison with recently published works [1-15].

We determine spatio-temporal distributions of concentrations of radiation defects by solving the following boundary problem [13,15]

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

Boundary and initial conditions for these equations are

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

Here $\rho = I, V$. The function $I(x,y,z,t)$ describes the spatio-temporal distribution of concentration of radiation interstitials. The functions $D_\rho(x,y,z,T)$ describes the approximations of diffusion coefficients of point radiation defects. Terms $V^2(x,y,z,t)$ and $I^2(x,y,z,t)$ correspond to generation divacancies and diinterstitials. The function $k_{I,V}(x,y,z,T)$ describes the parameter of recombination of point radiation defects. The functions $k_{I,I}(x,y,z,T)$ and $k_{V,V}(x,y,z,T)$ describe the parameters of generation of simplest complexes of point radiation defects.

Now we calculate distributions of concentrations of divacancies $\Phi_I(x,y,z,t)$ and diinterstitials $\Phi_V(x,y,z,t)$ in space and time by solving the following boundary problem [13,15]

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

$$\begin{aligned}
\frac{\partial \Phi_V(x, y, z, t)}{\partial t} &= \frac{\partial}{\partial x} \left[D_{\Phi_V}(x, y, z, T) \frac{\partial \Phi_V(x, y, z, t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_{\Phi_V}(x, y, z, T) \frac{\partial \Phi_V(x, y, z, t)}{\partial y} \right] + \\
&+ \frac{\partial}{\partial z} \left[D_{\Phi_V}(x, y, z, T) \frac{\partial \Phi_V(x, y, z, t)}{\partial z} \right] + k_{V,V}(x, y, z, T) V^2(x, y, z, t) - k_V(x, y, z, T) V(x, y, z, t), \\
\left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial x} \right|_{x=0} &= 0, \left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial x} \right|_{x=L_x} = 0, \left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial y} \right|_{y=0} = 0, \left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial y} \right|_{y=L_y} = 0, \\
\left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial z} \right|_{z=0} &= 0, \left. \frac{\partial \Phi_\rho(x, y, z, t)}{\partial z} \right|_{z=L_z} = 0, \Phi_I(x, y, z, 0) = f_{\Phi_I}(x, y, z), \Phi_V(x, y, z, 0) = f_{\Phi_V}(x, y, z). \quad (7)
\end{aligned}$$

The functions $D_{\Phi\rho}(x, y, z, T)$ describe the diffusion coefficients of the above complexes of radiation defects. The functions $k_I(x, y, z, T)$ and $k_V(x, y, z, T)$ describe the parameters of decay of these complexes. In this situation boundary problems Eqs.(4)-(7) are generalization of analogous problems in [13-15].

We determine distribution of temperature in space and time as solution of the second law of Fourier [14]

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

Boundary and initial conditions for the Eq. (8) are

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

Function $T(x, y, z, t)$ describes distribution of temperature in space and time during annealing of dopant and/or radiation defects. Function $c(T) = c_{ass}[1 - \eta \exp(-T(x, y, z, t)/T_d)]$ describes dependence of the heat capacitance on temperature. In the considered situation current temperature is approximately equal or larger, than Debye temperature T_d . In this situation we have a possibility to consider the following limiting case $c(T) \approx c_{ass}$ [14]. The function λ describes the heat conduction coefficient. The heat conduction coefficient depends on properties of materials and temperature and could be approximated by the following function $\lambda(x, y, z, T) = \lambda_{ass}(x, y, z)[1 + \mu(T_d/T(x, y, z, t))^q]$ [14]). The function describes $p(x, y, z, t)$ is the volumetric density of power of heating; $\alpha(x, y, z, T) = \lambda(x, y, z, T)/c(T)$ is the thermal diffusivity.

We calculate distribution of concentrations of dopant and radiation defects and temperature in space and time by method of averaging of function corrections [16-18] with decreasing quantity of iteration steps [17]. To use the approach we consider solutions of Eqs. (1), (4), (6), (8) 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

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

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

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

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

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

$$T_1(x, y, z, t) = \frac{1}{L_x L_y L_z} + \frac{2}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nT} c_n(x) c_n(y) c_n(z) e_{nT}(t),$$

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

$$e_{nT}(t) = \exp \left[-\pi^2 n^2 \alpha_0 t \left(\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2} \right) \right], \quad c_n(\chi) = \cos(\pi n \chi / L_{\chi}).$$

One could calculate approximations of the second- and other orders framework classical iteration procedure of method of averaging of function corrections [16-18]. Framework this procedure to determine the n -th-order approximation of concentrations of dopant and radiation defects we shall replace the required functions $C(x, y, z, t)$, $I(x, y, z, t)$, $V(x, y, z, t)$, $\Phi_I(x, y, z, t)$, $\Phi_V(x, y, z, t)$ and $T(x, y, z, t)$ in the right sides of Eqs. (1), (4), (6), (8) 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

$$\begin{aligned} \frac{\partial C_2(x, y, z, t)}{\partial t} &= \frac{\partial}{\partial x} \left(D_L(x, y, z, T) \left[1 + \zeta_1 \frac{V(x, y, z, t)}{V^*} + \zeta_2 \frac{V^2(x, y, z, t)}{(V^*)^2} \right] \frac{\partial C_1(x, y, z, t)}{\partial x} \right) \times \\ &\times \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^{\gamma}}{P^{\gamma}(x, y, z, T)} \right\} + \frac{\partial}{\partial y} \left(D_L(x, y, z, T) \left[1 + \zeta_1 \frac{V(x, y, z, t)}{V^*} + \zeta_2 \frac{V^2(x, y, z, t)}{(V^*)^2} \right] \right) \times \\ &\times \left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^{\gamma}}{P^{\gamma}(x, y, z, T)} \right\} \frac{\partial C_1(x, y, z, t)}{\partial y} + \frac{\partial}{\partial z} \left(\left\{ 1 + \xi \frac{[\alpha_{2C} + C_1(x, y, z, t)]^{\gamma}}{P^{\gamma}(x, y, z, T)} \right\} \times \right. \\ &\times \left. D_L(x, y, z, T) \left[1 + \zeta_1 \frac{V(x, y, z, t)}{V^*} + \zeta_2 \frac{V^2(x, y, z, t)}{(V^*)^2} \right] \frac{\partial C_1(x, y, z, t)}{\partial z} \right) \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{\partial I_2(x, y, z, t)}{\partial t} &= \frac{\partial}{\partial x} \left[D_I(x, y, z, T) \frac{\partial I_1(x, y, z, t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_I(x, y, z, T) \frac{\partial I_1(x, y, z, t)}{\partial y} \right] + \\ &+ \frac{\partial}{\partial z} \left[D_I(x, y, z, T) \frac{\partial I_1(x, y, z, t)}{\partial z} \right] - k_{I,V}(x, y, z, T) [\alpha_{2I} + I_1(x, y, z, t)] [\alpha_{2V} + V_1(x, y, z, t)] - \\ &- k_{I,I}(x, y, z, T) [\alpha_{2I} + I_1(x, y, z, t)]^2 \end{aligned} \quad (11)$$

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

$$\begin{aligned} \frac{\partial \Phi_{I2}(x, y, z, t)}{\partial t} &= \frac{\partial}{\partial x} \left[D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, t)}{\partial x} \right] + k_{I,I}(x, y, z, T) I^2(x, y, z, t) + \\ &+ \frac{\partial}{\partial y} \left[D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, t)}{\partial y} \right] + \frac{\partial}{\partial z} \left[D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, t)}{\partial z} \right] - \\ &- k_I(x, y, z, T) I(x, y, z, t) \end{aligned} \quad (12)$$

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

$$\begin{aligned} c \frac{\partial T_2(x, y, z, t)}{\partial t} &= \frac{\partial}{\partial x} \left(\lambda_{ass}(x, y, z) \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, t)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, t)]}{\partial x} \right) + \\ &+ \frac{\partial}{\partial y} \left(\lambda_{ass}(x, y, z) \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, t)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, t)]}{\partial y} \right) + \\ &+ \frac{\partial}{\partial z} \left(\lambda_{ass}(x, y, z) \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, t)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, t)]}{\partial z} \right) + p(x, y, z, t). \end{aligned} \quad (13)$$

Integration of both sides of Eqs. (10)-(13) on time gives us possibility to obtain relations for the second-order approximations of the required concentrations in the final form

$$\begin{aligned}
 C_2(x, y, z, t) = & \frac{\partial}{\partial x} \left[\int_0^t D_L(x, y, z, T) \left[1 + \varsigma_1 \frac{V(x, y, z, \tau)}{V^*} + \varsigma_2 \frac{V^2(x, y, z, \tau)}{(V^*)^2} \right] \frac{\partial C_1(x, y, z, \tau)}{\partial x} \times \right. \\
 & \times \left. \left\{ 1 + \xi \frac{[\alpha_{2c} + C_1(x, y, z, \tau)]^\gamma}{P^\gamma(x, y, z, T)} \right\} \right] d\tau + \frac{\partial}{\partial y} \left(\int_0^t \left[1 + \varsigma_1 \frac{V(x, y, z, \tau)}{V^*} + \varsigma_2 \frac{V^2(x, y, z, \tau)}{(V^*)^2} \right] \times \right. \\
 & \times D_L(x, y, z, T) \left\{ 1 + \xi \frac{[\alpha_{2c} + C_1(x, y, z, \tau)]^\gamma}{P^\gamma(x, y, z, T)} \right\} \frac{\partial C_1(x, y, z, \tau)}{\partial y} d\tau \Bigg) + \frac{\partial}{\partial z} \left(\int_0^t \frac{\partial C_1(x, y, z, \tau)}{\partial z} \times \right. \\
 & \times D_L(x, y, z, T) \left[1 + \varsigma_1 \frac{V(x, y, z, \tau)}{V^*} + \varsigma_2 \frac{V^2(x, y, z, \tau)}{(V^*)^2} \right] d\tau \Bigg) + f_c(x, y, z) \quad (10a)
 \end{aligned}$$

$$\begin{aligned}
 I_2(x, y, z, t) = & \frac{\partial}{\partial x} \left[\int_0^t D_I(x, y, z, T) \frac{\partial I_1(x, y, z, \tau)}{\partial x} d\tau \right] + \frac{\partial}{\partial y} \left[\int_0^t D_I(x, y, z, T) \frac{\partial I_1(x, y, z, \tau)}{\partial y} d\tau \right] + \\
 & + \frac{\partial}{\partial z} \left[\int_0^t D_I(x, y, z, T) \frac{\partial I_1(x, y, z, \tau)}{\partial z} d\tau \right] - \int_0^t k_{I,I}(x, y, z, T) [\alpha_{2I} + I_1(x, y, z, \tau)]^2 d\tau - \\
 & - \int_0^t k_{I,V}(x, y, z, T) [\alpha_{2I} + I_1(x, y, z, \tau)] [\alpha_{2V} + V_1(x, y, z, \tau)] d\tau + f_I(x, y, z) \quad (11a)
 \end{aligned}$$

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

$$\begin{aligned}
 \Phi_{I2}(x, y, z, t) = & \frac{\partial}{\partial x} \left[\int_0^t D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, \tau)}{\partial x} d\tau \right] - \int_0^t k_I(x, y, z, T) I(x, y, z, \tau) d\tau + \\
 & + \frac{\partial}{\partial y} \left[\int_0^t D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, \tau)}{\partial y} d\tau \right] + \frac{\partial}{\partial z} \left[\int_0^t D_{\Phi I}(x, y, z, T) \frac{\partial \Phi_{I1}(x, y, z, \tau)}{\partial z} d\tau \right] + \\
 & + \int_0^t k_{I,I}(x, y, z, T) I^2(x, y, z, \tau) d\tau + f_{\Phi I}(x, y, z) \quad (12a)
 \end{aligned}$$

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

$$\begin{aligned}
 & + \frac{\partial}{\partial y} \left[\int_0^t D_{\Phi V}(x, y, z, T) \frac{\partial \Phi_{V1}(x, y, z, \tau)}{\partial y} d\tau \right] + \frac{\partial}{\partial z} \left[\int_0^t D_{\Phi V}(x, y, z, T) \frac{\partial \Phi_{V1}(x, y, z, \tau)}{\partial z} d\tau \right] + \\
 & + \int_0^t k_{V,V}(x, y, z, T) V^2(x, y, z, \tau) d\tau + f_{\Phi V}(x, y, z), \\
 & cT(x, y, z, t) = \frac{\partial}{\partial x} \left(\lambda_{ass}(x, y, z) \int_0^t \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, \tau)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, \tau)]}{\partial x} d\tau \right) + \\
 & + f_T(x, y, z) + \frac{\partial}{\partial y} \left(\lambda_{ass}(x, y, z) \int_0^t \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, \tau)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, \tau)]}{\partial y} d\tau \right) + \quad (13a) \\
 & + \frac{\partial}{\partial z} \left(\lambda_{ass}(x, y, z) \int_0^t \left\{ 1 + \mu \left[\frac{T_d}{T(x, y, z, \tau)} \right]^\varphi \right\} \frac{\partial [\alpha_{2T} + T_1(x, y, z, \tau)]}{\partial z} d\tau \right) + \int_0^t p(x, y, z, \tau) d\tau.
 \end{aligned}$$

One could calculate average values of the second-orders approximations of the required concentrations and temperature by the standard relation [16-18]

$$\alpha_{2\rho} = \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} [\rho_2(x, y, z, t) - \rho_1(x, y, z, t)] dz dy dx dt. \quad (14)$$

Final relations for the required average values by substitution of the relations (10a)-(13a) into the relation (14)

$$\alpha_{2c} = \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_c(x, y, z) dz dy dx, \quad (15)$$

$$\begin{aligned}
 \alpha_{2I} = \frac{1}{2A_{H00}} & \left\{ (1 + A_{IV01} + A_{H10} + \alpha_{2V} A_{IV00})^2 - 4A_{H00} [\alpha_{2V} A_{IV10} - A_{H20} + A_{IV11} - \right. \\
 & \left. - \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_I(x, y, z) dz dy dx \right\}^{\frac{1}{2}} - \frac{1 + A_{IV01} + A_{H10} + \alpha_{2V} A_{IV00}}{2A_{H00}}, \quad (16)
 \end{aligned}$$

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

Parameters A_{abij} and other parameters in the relations (16) are presented in the Appendix. Parameters α_{abij} and other parameters in the relations (16) could be written as

$$\begin{aligned}
 \alpha_{2\Phi_I} = A_{H20} - \frac{1}{\Theta L_x L_y L_z} & \int_0^{\Theta} (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} k_I(x, y, z, T) I(x, y, z, t) dz dy dx dt + \\
 & + \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_{\Phi I}(x, y, z) dz dy dx \quad (17)
 \end{aligned}$$

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

$$+ \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_{\Phi_V}(x, y, z) dz dy dx.$$

The above substitution leads to obtaining equation for parameter α_{2C} . Solution of the equation will be different for different values of parameter γ . We used the second-order approximations framework method of averaging of function corrections with decreased quantity of iterative steps for analysis of spatio-temporal distributions of concentrations of dopant and radiation defects and temperature. The second-order approximation is usually a sufficient approximation to obtain qualitative and some quantitative results. We checked our analytical results by numerical approaches.

3. Discussion

Based on recently calculated relations we analyzed redistribution of dopant and radiation defects. Figures 2a and 2b show distributions of concentrations of infused (Fig. 2a) and implanted (Fig. 2b) dopants in channels and in nearest areas. We calculate the above distribution for larger value of dopant diffusion coefficient in doped materials in comparison with the analogous coefficient in undoped area. 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. In this situation one can obtain increasing density of electrical 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. Figs. 3 are illustrations of this situations. We used recently introduced criterion [9,10,18-24] to determine optimal value of annealing time. Framework the criterion we approximate real distribution of concentration of dopant by idealized step-wise function $\psi(x, y, z)$. Framework the criterion we minimize the following mean-squared error to determine the optimal value of annealing time

$$U = \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} [C(x, y, z, \Theta) - \psi(x, y, z)]^2 dz dy dx. \quad (18)$$

Fig. 2a. Spatial distributions of concentrations of infused dopant. Coordinate x is perpendicular to interface between layers of heterostructure. Difference between values of dopant diffusion coefficient in layers of heterostructure increases with increasing of number of distributions.

Fig. 2b. Spatial distributions of concentrations of infused dopant. Distributions 1 and 2 have been calculated in homogenous material 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). Distributions 3 and 4 have been calculated for heterostructure with two layers for the same annealing time

The considered distributions in Figs. 2 corresponds exactly to compromise annealing time.

Fig.3a. Distributions of concentration of infused dopant on coordinate for different values of annealing time. Value of annealing time increases with increasing of number of curves

Fig.3a. Distributions of concentration of implanted dopant on coordinate for different values of annealing time. Value of annealing time increases with increasing of number of curves

4. 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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APPENDIX

$$\begin{aligned}
 A_{abij} &= \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta} (\Theta - t) \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} k_{a,b}(x, y, z, T) I_1^i(x, y, z, t) V_1^j(x, y, z, t) dz dy dx dt, \\
 B_4 &= A_{IV00}^2 A_{IV00}^2 - 2(A_{IV00}^2 - A_{II00} A_{VV00})^2, \quad B_3 = A_{IV00} A_{IV00}^2 + A_{IV01} A_{IV00}^3 + A_{IV00} A_{II10} A_{IV00}^2 - \\
 &- 4(A_{IV00}^2 - A_{II00} A_{VV00}) [2A_{IV01} A_{IV00} + 2A_{IV00} (1 + A_{IV01} + A_{II10}) - 2A_{II00} (A_{IV10} + A_{VV10} + 1)] - \\
 &- 4A_{IV10} A_{IV10} A_{II00} A_{IV00}^2 + 2A_{IV00} A_{IV01} A_{IV00}^2, \quad B_2 = A_{IV00}^2 \{ (1 + A_{IV01} + A_{II10})^2 + A_{IV00}^2 A_{IV01}^2 - A_{II00} \times \\
 &\times 4 \left[A_{IV11} - A_{II20} - \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_I(x, y, z) dz dy dx \right] + 2A_{IV00} A_{IV01} (A_{IV00} + A_{IV00} A_{IV01} + \\
 &+ A_{IV00} A_{II10} - 4A_{IV10} A_{II00}) \} [2A_{IV01} A_{IV00} + 2A_{IV00} (1 + A_{IV01} + A_{II10}) - 2A_{II00} (A_{IV10} + A_{VV10} + \\
 &+ 1)]^2 + 2 \left[A_{IV01} (1 + A_{IV01} + A_{II10}) + \frac{2}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_V(x, y, z) dz dy dx - 2(A_{VV20} - A_{IV11}) \times \right. \\
 &\times A_{II00} + A_{IV01} (1 + A_{IV01} + A_{II10}) \} [2A_{IV00} (1 + A_{IV01} + A_{II10}) - 2A_{II00} (A_{IV10} + A_{VV10} + 1) + \\
 &+ 2A_{IV01} A_{IV00}] \}, \quad B_1 = 2A_{IV00} A_{IV01} (1 + A_{IV01} + A_{II10})^2 - 8A_{IV00} A_{IV01} A_{II00} [A_{IV11} - A_{II20} - \\
 &- \frac{1}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_I(x, y, z) dz dy dx] + (A_{IV00} + A_{IV00} A_{IV01} + A_{IV00} A_{II10} - 4A_{IV10} A_{II00}) \times \\
 &\times A_{IV01}^2 - 2 \left[\frac{2A_{II00}}{L_x L_y L_z} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} f_I(x, y, z) dz dy dx + A_{IV01} (1 + A_{IV01} + A_{II10}) - (A_{VV20} - A_{IV11}) \times \right.
 \end{aligned}$$

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