MODELING OF MANUFACTURING OF A FIELD-EFFECT TRANSISTOR TO DETERMINE CONDITIONS TO DECREASE LENGTH OF CHANNEL

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ABSTRACT

In this paper we introduce an approach to model technological process of manufacture of a field-effect heterotransistor. The modeling gives us possibility to optimize the technological process to decrease length of channel by using mechanical stress. As accompanying results of the decreasing one can find decreasing of thickness of the heterotransistors and increasing of their density, which were comprised in integrated circuits.

KEYWORDS

Modelling of manufacture of a field-effect heterotransistor, Accounting mechanical stress; Optimization the technological process, Decreasing length of channel

1. INTRODUCTION

One of intensively solved problems of the solid-state electronics is decreasing of elements of integrated circuits and their discrete analogs [1-7]. To solve this problem attracted an interest widely used laser and microwave types of annealing [8-14]. These types of annealing leads to generation of inhomogeneous distribution of temperature. In this situation one can obtain increasing of sharpness of p-n-junctions with increasing of homogeneity of dopant distribution in enriched area [8-14]. The first effects give us possibility to decrease switching time of p-n-junction and value of local overheats during operating of the device or to manufacture more shallow p-n-junction with fixed maximal value of local overheats. An alternative approach to laser and microwave types of annealing one can use native inhomogeneity of heterostructure and optimization of annealing of dopant and/or radiation defects to manufacture diffusive –junction and implanted-junction rectifiers [12-18]. It is known, that radiation processing of materials is also leads to modification of distribution of dopant concentration [19]. The radiation processing could be also used to increase of sharpness of p-n-junctions with increasing of homogeneity of dopant distribution in enriched area [20, 21]. Distribution of dopant concentration is also depends on mechanical stress in heterostructure [15].

In this paper we consider a field-effect heterotransistor. Manufacturing of the transistor based on combination of main ideas of Refs. [5] and [12-18]. Framework the combination we consider a heterostructure with a substrate and an epitaxial layer with several sections. Some dopants have been infused or implanted into the section to produce required types of conductivity. Farther we
consider optimal annealing of dopant and/or radiation defects. Manufacturing of the transistor has been considered in details in Ref. [17]. Main aim of the present paper is analysis of influence of mechanical stress on length of channel of the field-effect transistor.

To solve our aim we determine spatio-temporal distribution of concentration of dopant in the considered heterostructure and make the analysis. We determine spatio-temporal distribution of concentration of dopant with account mechanical stress by solving the second Fick’s law [1-4,22,23]. We assume to simplify illustration our main results, that we have possibility to use rectangular coordinate system. In this situation the second Fick’s law could be written as
\[ \frac{\partial C(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x} \left[ D \frac{\partial C(x,y,z,t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D \frac{\partial C(x,y,z,t)}{\partial y} \right] + \frac{\partial}{\partial z} \left[ D \frac{\partial C(x,y,z,t)}{\partial z} \right] + \frac{\partial}{\partial x} \left[ \frac{D_s}{kT} \nabla_s \mu (x,y,z,t) \right] C(x,y,W,t) dW + \frac{\partial}{\partial y} \left[ \frac{D_s}{kT} \nabla_s \mu (x,y,z,t) \right] C(x,y,W,t) dW \]

with boundary and initial conditions

\[ \frac{\partial C(x,y,z,t)}{\partial x} \bigg|_{x=0} = 0, \quad \frac{\partial C(x,y,z,t)}{\partial x} \bigg|_{x=L_x} = 0, \quad \frac{\partial C(x,y,z,t)}{\partial y} \bigg|_{y=0} = 0, \quad \frac{\partial C(x,y,z,t)}{\partial y} \bigg|_{y=L_y} = 0, \quad \frac{\partial C(x,y,z,t)}{\partial z} \bigg|_{z=0} = 0, \quad \frac{\partial C(x,y,z,t)}{\partial z} \bigg|_{z=L_z} = 0, \quad C(x,y,z,0)=f_e(x,y,z). \]

Here \( C(x,y,z,t) \) is the spatio-temporal distribution of concentration of dopant; \( \Omega \) is the atomic volume; \( \nabla_s \) is the operators of surficial gradient; \( L_z \) is the surficial concentration of dopant on interface between layers of heterostructure; \( \mu (x,y,z,t) \) is the chemical potential; \( D \) and \( D_s \) are coefficients of volumetric and surficial (due to mechanical stress) of diffusion. Zero values of derivatives on external boundaries of heterostructure corresponds to absence of dopant flow through the boundaries. The first, the second and the third terms of the Eq.(1) correspond to free diffusion of atoms of dopant in three directions: \( x, y, \) and \( z, \) respectively \([1,3,6,12-21]\). Two last terms of the Eq.(1) correspond to moving of atoms of dopant under influence of mechanical stress \([22]\). Values of the diffusion coefficients depend on properties of materials of heterostructure, speed of heating and cooling of heterostructure, spatio-temporal distribution of concentration of dopant. Concentraional dependence of dopant diffusion coefficients have been approximated by the following relations \([24]\)

\[ D = D_i(x,y,z,T) \left[ 1 + \frac{\xi}{P^i(x,y,z,T)} C^i(x,y,z,t) \right], \quad D_s = D_{sL}(x,y,z,T) \left[ 1 + \frac{\xi}{P^i(x,y,z,T)} C^i(x,y,z,t) \right], \quad (2) \]

Here \( D_i(x,y,z,T) \) and \( D_{sL}(x,y,z,T) \) are the spatial (due to inhomogeneity of heterostructure) and the temperature (due to Arrhenius law) dependences of dopant diffusion coefficients; \( T \) is the temperature of annealing; \( P(x,y,z,T) \) is the limit of solubility of dopant; parameter \( \gamma \) could be interger in the following interval \( \gamma \in [1,3] \) \([24]\). Concentraional dependence of dopant diffusion coefficients has been discussed in details in \([24]\). Chemical potential could be determine by the following relation \([22]\)

\[ \mu=E(z)\Omega \sigma_g[u_0(x,y,z,t)+u_0(x,y,z,t)]/2, \quad (3) \]

where \( E \) is the Young modulus; \( \sigma_g \) is the stress tensor; \( u_g = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the deformation tensor \([22,23]\); \( u_i, u_j \) are the components \( u(x,y,z,t), u(y,x,z,t) \) and \( u(x,y,z,t) \) of the displacement vector \( \bar{u}(x,y,z,t) \); \( x, x_j \) are the coordinates \( x, y, z \). Relation (3) could be transform to the following form \([23]\)
\[ \mu(x,y,z,t) = \left[ \frac{\partial u_x(x,y,z,t)}{\partial x} + \frac{\partial u_y(x,y,z,t)}{\partial y} \right] \left[ \frac{1}{2} \left[ \frac{\partial u_x(x,y,z,t)}{\partial x} + \frac{\partial u_y(x,y,z,t)}{\partial y} \right] \times \right. \\
\left. \times \frac{E(z)}{2} - E_0 \delta_0 + \frac{\sigma(z) \delta_0}{1-2\sigma(z)} \left[ \frac{\partial u_x(x,y,z,t)}{\partial x} \right] - K(z) \beta(z) [T(x,y,z,t) - T'_0] \delta_0 \right], \quad (3a) \]

where \( \sigma \) is the Poisson coefficient; \( \varepsilon_0 = (a_r - a_{EL})/a_{EL} \) is the mismatch strain; \( a_r \), \( a_{EL} \) are the lattice spacings for substrate and epitaxial layer, respectively; \( K \) is the modulus of uniform compression; \( \beta \) is the coefficient of thermal expansion; \( T_r \) is the equilibrium temperature, which coincide (for our case) with room temperature. Components of displacement vector could be obtained by solving of the following equations [23]

\[
\begin{align*}
\rho(z) \frac{\partial^2 u_x(x,y,z,t)}{\partial t^2} &= \frac{\partial \sigma_x(x,y,z,t)}{\partial x} + \frac{\partial \sigma_y(x,y,z,t)}{\partial y} + \frac{\partial \sigma_z(x,y,z,t)}{\partial z} \\
\rho(z) \frac{\partial^2 u_y(x,y,z,t)}{\partial t^2} &= \frac{\partial \sigma_x(x,y,z,t)}{\partial x} + \frac{\partial \sigma_y(x,y,z,t)}{\partial y} + \frac{\partial \sigma_z(x,y,z,t)}{\partial z} \\
\rho(z) \frac{\partial^2 u_z(x,y,z,t)}{\partial t^2} &= \frac{\partial \sigma_x(x,y,z,t)}{\partial x} + \frac{\partial \sigma_y(x,y,z,t)}{\partial y} + \frac{\partial \sigma_z(x,y,z,t)}{\partial z}
\end{align*}
\]

where \( \sigma_0 = \frac{E(z)}{2[1+\sigma(z)]} \left[ \frac{\partial u_x(x,y,z,t)}{\partial x} + \frac{\partial u_y(x,y,z,t)}{\partial y} \right] - \frac{\delta_0}{3} \frac{\partial u_x(x,y,z,t)}{\partial x} + \frac{\delta_0}{\partial x} \times \\
\times K(z) - \beta(z) K(z) [T(x,y,z,t) - T'_0], \rho(z) \) is the density of materials, \( \delta_0 \) is the Kronecker symbol.

Accounting the relation (3a) into the above equations gives us possibility to transform the equations to the following form

\[
\rho(z) \frac{\partial^2 u_x(x,y,z,t)}{\partial t^2} = \left[ K(z) + \frac{SE(z)}{6[1+\sigma(z)]} \right] \frac{\partial^2 u_x(x,y,z,t)}{\partial x^2} + \left[ K(z) - \frac{E(z)}{3[1+\sigma(z)]} \right] \frac{\partial^2 u_x(x,y,z,t)}{\partial x \partial y} + \\
+ \frac{E(z)}{2[1+\sigma(z)]} \left[ \frac{\partial^2 u_x(x,y,z,t)}{\partial y^2} + \frac{\partial^2 u_x(x,y,z,t)}{\partial z^2} \right] + \left[ K(z) + \frac{E(z)}{3[1+\sigma(z)]} \right] \frac{\partial^2 u_x(x,y,z,t)}{\partial x \partial z} - K(z) \times \\
\times \beta(z) \frac{\partial T(x,y,z,t)}{\partial x}
\]

\[
\rho(z) \frac{\partial^2 u_y(x,y,z,t)}{\partial t^2} = \left[ \frac{E(z)}{2[1+\sigma(z)]} \right] \left[ \frac{\partial^2 u_y(x,y,z,t)}{\partial x^2} + \frac{\partial^2 u_y(x,y,z,t)}{\partial x \partial y} \right] - \beta(z) K(z) \frac{\partial T(x,y,z,t)}{\partial y} + \\
+ \frac{\partial}{\partial z} \left[ \frac{E(z)}{2[1+\sigma(z)]} \right] \left[ \frac{\partial u_x(x,y,z,t)}{\partial z} + \frac{\partial u_y(x,y,z,t)}{\partial y} \right] + \left[ \frac{SE(z)}{12[1+\sigma(z)]} + K(z) \right] \frac{\partial^2 u_y(x,y,z,t)}{\partial y^2} + 
\]
Farther let us analyze spatio-temporal distribution of temperature as solution of the second law of Fourier.

\[ \frac{\partial}{\partial t} \left( \frac{\partial E}{\partial t} \right) = \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] + \frac{\partial}{\partial z} \left[ K \left( \frac{\partial u}{\partial z} \right) \right] \times \frac{E(z)}{2 + \sigma(z)} + \rho \left( \frac{\partial u}{\partial z} \right) \times K(\beta) \left( \frac{\partial u}{\partial z} \right), \]

where \( E(z) \) is the Debye temperature, and \( \rho \) is the density of the material.

Conditions for the displacement vector could be written as

\[ \frac{\partial \bar{u}(0,y,z,t)}{\partial x} = 0; \quad \frac{\partial \bar{u}(L_x,y,z,t)}{\partial x} = 0; \quad \frac{\partial \bar{u}(x,0,z,t)}{\partial y} = 0; \quad \frac{\partial \bar{u}(x,L_y,z,t)}{\partial y} = 0; \]

\[ \frac{\partial \bar{u}(x,y,0,t)}{\partial z} = 0; \quad \frac{\partial \bar{u}(x,y,L_z,t)}{\partial z} = 0; \quad \bar{u}(x,y,z,0) = \bar{u}_0; \quad \bar{u}(x,y,z,\infty) = \bar{u}_0. \]

Zero values of derivatives on external boundaries of heterostructure corresponds to absence of correspond to the same situation as in the conditions for dopant. Farther let us analyze spatio-temporal distribution of temperature during annealing of dopant. We determine spatio-temporal distribution of temperature as solution of the second law of Fourier [25]

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

with boundary and initial conditions

\[ \frac{\partial T(x,y,z,t)}{\partial x} \bigg|_{x=0} = 0, \quad \frac{\partial T(x,y,z,t)}{\partial x} \bigg|_{x=L_x} = 0, \quad \frac{\partial T(x,y,z,t)}{\partial y} \bigg|_{y=0} = 0, \quad \frac{\partial T(x,y,z,t)}{\partial y} \bigg|_{y=L_y} = 0, \]

\[ \frac{\partial T(x,y,z,t)}{\partial z} \bigg|_{z=0} = 0, \quad \frac{\partial T(x,y,z,t)}{\partial z} \bigg|_{z=L_z} = 0, \quad T(x,y,z,0) = T_0(x,y,z). \]

Here \( \lambda \) is the heat conduction coefficient. Value of the coefficient depends on materials of heterostructure and temperature. Temperature dependence of heat conduction coefficient in most interest area could be approximated by the following function: \( \lambda(x,y,z,T) = \lambda_{ss}(x,y,z)[1 + \mu T/T_0] \) (see, for example, [25]). \( c(T) = c_{ss}[1 - \beta \exp(-T_s/T_0)] \) is the heat capacitance; \( T_d \) is the Debye temperature [25]. The temperature \( T(x,y,z,t) \) is approximately equal or larger, than Debye temperature \( T_d \) for most interesting for us temperature interval. In this situation one can write the following approximate relation: \( c(T) = c_{ss}, p(x,y,z,t) \) in the last term of Eq.(4) is the
First of all we calculate spatio-temporal distribution of temperature. We calculate spatio-temporal distribution of temperature by using recently introduce approach [15, 17,18]. Framework the approach we transform approximation of thermal diffusivity \( \alpha_{\text{ass}}(x,y,z) = \lambda_{\text{ass}}(x,y,z) / \rho_{\text{ass}} = \alpha_{\text{ass}}[1 + \varepsilon \tau g_T(x,y,z)] \). Farther we determine solution of Eqs. (5) as the following power series

\[
T(x,y,z,t) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \mu T_{ij}(x,y,z,t).
\]  

Substitution of the series into Eq.(6) gives us possibility to obtain system of equations for the initial-order approximation of temperature \( T_{00}(x,y,z,t) \) and corrections for them \( T_{ij}(x,y,z,t) \) \((i \geq 1, j \geq 1)\). The procedure has been described in details in [12-14,18]. In this situation we will not present the procedure in this paper. Substitution of the series (6) in boundary and initial conditions for spatio-temporal distribution of temperature gives us possibility to obtain boundary and initial conditions for the functions \( T_{ij}(x,y,z,t) \) \((i \geq 0, j \geq 0)\). The procedure has been described in details in [12-14,18] and will not be presented here. Solutions of the equations for the functions \( T_{ij}(x,y,z,t) \) \((i \geq 0, j \geq 0)\) have been obtained as the second-order approximation on the parameters \( \varepsilon \) and \( \mu \) by standard approaches [28,29] and will not be presented in the paper. Recently we obtain, that the second-order approximation is enough good approximation to make qualitative analysis and to obtain some quantitative results (see, for example, [15,17,18]). Analytical results have allowed to identify and to illustrate the main dependence. To check our results obtained we used numerical approaches.

Farther let us estimate components of the displacement vector. The components could be obtained by using the same approach as for calculation distribution of temperature. However, relations for components could be calculated in shorter form by method of averaging of function corrections [12-14,16,27]. It is practically to transform differential equations of system (4) to integro-differential form. The integral equations are presented in the Appendix. We determine the first-order approximations of components of the displacement vector by replacement the required functions \( u_{\alpha\beta}(x,y,z,t) \) on their average values \( \alpha_{\alpha\beta} \). The average values \( \alpha_{\alpha\beta} \) have been calculated by the following relations

\[
\alpha_{\alpha\beta} = M_{s,ij} / 4L\Theta,
\]  

where \( M_{s,ij} = \int_{-L_z}^{L_z} \int_{-L_y}^{L_y} \int_{-L_x}^{L_x} u_{ij}(x,y,z,t) \, dz \, dy \, dx \, dt \). The replacement leads to the following results

\[
u_{s,ij}(x,y,z,t) = \int_{0}^{t} \left[ K(w)\alpha(w) \frac{\partial T(x,y,w,\tau)}{\partial x} \right] dw \, d\tau - \int_{0}^{t} \left[ K(w)\beta(w) \frac{\partial T(x,y,w,\tau)}{\partial x} \right] dw \, d\tau -
\]
\[-\alpha_{m1} \Phi_{m0}(x, y, w, t)] \phi + \alpha_{m1},
\]

\[u_{x}(x, y, z, t) = \left[ \tau \int_{0}^{\tau} K(w) \alpha(w) \frac{\partial T}{\partial y} d \tau + \int_{0}^{\tau} K(w) \beta(w) \frac{\partial T}{\partial y} d \tau \right] + \left[ \tau \int_{0}^{\tau} K(w) \alpha(w) \frac{\partial T}{\partial w} d \tau + \int_{0}^{\tau} K(w) \beta(w) \frac{\partial T}{\partial w} d \tau \right] - \alpha_{m1} \Phi_{m0}(x, y, w, t)] \phi + \alpha_{m1},\]

Substitution of the above relations into relations (7) gives us possibility to obtain values of the parameters \(\alpha_{\beta1}\). Appropriate relations could be written as

\[\alpha_{m1} = \frac{L_{z}[X_{z,0}(\infty) - X_{z,1}(\Theta)]}{8L \int_{0}^{L_{z}} (L_{z} - z) \rho(z) d z}, \quad \alpha_{\beta1} = \frac{L_{z}[X_{z,0}(\infty) - X_{z,1}(\Theta)]}{8L \int_{0}^{L_{z}} (L_{z} - z) \rho(z) d z}, \quad \alpha_{m1} = \frac{L_{z}[X_{z,0}(\infty) - X_{z,1}(\Theta)]}{8L \int_{0}^{L_{z}} (L_{z} - z) \rho(z) d z},\]

where \(X_{z,1}(\Theta) = \int_{0}^{\Theta} \int_{L_{z}-L_{z}}^{L_{z}} (L_{z} - z) K(z) \chi(z) \frac{\partial T}{\partial z} d z d y d x d \tau\).

The second-order approximations of components of the displacement vector by replacement of the required functions \(u_{x}(x, y, z, t)\) on the following sums \(\alpha_{m2} + u_{x2}(x, y, z, t)\), where \(\alpha_{m2} = (M_{m2} - M_{m1})/4L^{3} \Theta\). Results of calculations of the second-order approximations \(u_{x2}(x, y, z, t)\) and their average values \(\alpha_{m2}\) are will not be presented in this paper, because the procedure is standard.

Spatio-temporal distribution of concentration of dopant we obtain by solving the Eq.(1). To solve the equations we used recently introduce approach [15,17,18] and transform approximations of dopant diffusion coefficients \(D_{f}(x, y, z, T)\) and \(D_{SL}(x, y, z, T)\) to the following form: \(D_{f}(x, y, z, T) = D_{f0}[1 + \epsilon_{f}g_{f}(x, y, z, T)]\) and \(D_{SL}(x, y, z, T) = D_{SL}[1 + \epsilon_{SL}g_{SL}(x, y, z, T)]\). We also introduce the following dimensionless parameter: \(\omega = D_{SL}/D_{f0}\). In this situation the Eq.(1) takes the form

\[\partial C(x, y, z, t)/\partial t = D_{f0} \frac{\partial}{\partial x} \left[ 1 + \epsilon_{f}g_{f}(x, y, z, T) \right] \frac{\partial C(x, y, z, t)}{\partial x} + D_{f0} \frac{\partial}{\partial y} \left[ 1 + \epsilon_{f}g_{f}(x, y, z, T) \right] \frac{\partial C(x, y, z, t)}{\partial y} \times \]

\[\times \left[ 1 + \epsilon_{f}g_{f}(x, y, z, T) \right] \frac{\partial C(x, y, z, t)}{\partial z} + \omega D_{f0} \frac{\partial}{\partial x} \left[ 1 + \epsilon_{SL}g_{SL}(x, y, z, T) \right] \frac{\partial C(x, y, z, t)}{\partial x} + \frac{\partial C(x, y, z, t)}{\partial y} \times \]

\[\epsilon_{SL}g_{SL}(x, y, z, T) \frac{\partial C(x, y, z, t)}{\partial z} \times \partial C(x, y, z, t)/\partial z \]
We determine solution of Eq.(1) as the following power series

\[ C(x, y, z, t) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \alpha_i \beta_j \gamma_k \varphi_i(x, y, z, t) = 0. \]  

Substitution of the series into Eq.(8) gives us possibility to obtain systems of equations for initial-order approximation of concentration of dopant \( C_{000}(x, y, z, t) \) and corrections for them \( C_{ijk}(x, y, z, t) \) \((i \geq 1, j \geq 1, k \geq 1)\). The equations will not presented in this paper. Substitution of the series into appropriate boundary and initial conditions gives us possibility to obtain boundary and initial conditions for all functions \( C_{ijk}(x, y, z, t) \) \((i \geq 0, j \geq 0, k \geq 0)\). Solutions of equations for the functions \( C_{ijk}(x, y, z, t) \) \((i \geq 0, j \geq 0, k \geq 0)\) have been calculated by standard approaches [28,29] and will not presented in this paper.

Analysis of spatio-temporal distributions of concentrations of dopant and radiation defects has been done analytically by using the second-order approximations framework recently introduced power series. The approximation is enough good approximation to make qualitative analysis and to obtain some quantitative results. All obtained analytical results have been checked by comparison with results, calculated by numerical simulation.

![Fig. 3](image)

Fig. 3. Distributions of concentration of dopant in directions, which is perpendicular to interface between layers of heterostructure. Curve 1 is a dopant distribution in a homogenous sample. Curve 2 corresponds to negative value of the mismatch strain. Curve 3 corresponds to positive value of the mismatch strain

3. Discussion

In this section we analyzed redistribution of dopant under influence of mechanical stress based on relations calculated in previous section. Fig. 3 show spatio-temporal distribution of concentration of dopant in a homogenous sample (curve 1) and in heterostructure with negative and positive value of the mismatch strain \( \epsilon_0 \) (curve 2 and 3, respectively). The figure shows, that manufacturing field-effect heterotransistors gives us possibility to make more compact field-effect transistors in direction, which is parallel to interface between layers of heterostructure. As a consequence of the increasing of compactness one can obtain decreasing of length of channel of field- effect transistor and increasing of density of the transistors in integrated circuits. It should be noted, that presents of interface between layers of heterostructure give us possibility to manufacture more thin transistors [17].
4. Conclusion

In this paper we consider possibility to decrease length of channel of field-effect transistor by using mechanical stress in heterostructure. At the same time with decreasing of the length it could be increased density of transistors in integrated circuits.

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