An Approach to Decrease Dimensions of Field-Effect Transistors

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Abstract In this paper we consider an approach to manufacture a field-effect transistor. The approach gives us possibility to decrease dimensions of the transistor in two directions at expense of the third one. The increasing of the third dimension of the field-effect transistor did not compensate full volume of the transistor.

Keywords Field-Effect Transistor, Optimization of Technological Process, Analytical Approach to Model Technological Process

1. Introduction

In the present time intensive decreasing of dimensions of elements of integrated circuits (p-n-junctions, field-effect and bipolar transistors et al) and their discrete analogs is occur [1-9]. To decrease dimensions of elements of integrated circuits are could use laser and/or microwave types of annealing (this types of annealing are intensively elaborating [10-12]), unsoundness of doped structure (for example, due to radiation damage [13] and appropriate references in this paper) et al. In the present paper we consider a heterostructure, which consist of a substrate and two epitaxial layers (see Figs. 1 and 2). The epitaxial layers including into itself four areas, which have been manufacturing by using another materials with dimensions \(a_i\) (\(i=1\) or 2) (in direction, which is perpendicular to interface between layers of heterostructure), \(b_j\) (\(j=1, 2\) or 3) and \(c_k\) (\(k=1\) or 2). Two of these areas could be used as source and drain after appropriate doping. One or two dopants have been infused into the two areas to produce required types of conductivities (p or n). It has been recently shown, that interface between layers of heterostructure under specific conditions and optimization of annealing time give us possibility to produce more homogenous distribution of dopant in doped area and decreasing of dopant concentration with higher speed after the doped area (one of consequence of the modification of dopant distribution is increasing of sharpness of p-n-junction, another consequence is increasing of homogeneity of dopant distribution in enriched area) [14-16]. Increasing of sharpness of p-n-junctions gives us possibility to decrease their switching times. Increasing of homogeneity of dopant distribution in doped area of p-n-junctions gives us possibility to decrease value of local overheats during functioning of their devices. The considered approach for manufacturing a field-effect transistor gives us possibility to decrease dimensions of this type of transistors in comparison with approach considered in [16] and all the more with approach considered in [1]. Main aims of the present paper are description of introduced construction of field-effect transistor and optimization of annealing time.

2. Method of Solution

To solve our aims first of all we determine spatiotemporal distributions of concentrations of dopants. We determine the distributions by solving the second Fick’s low [8,9,13]
Figure 1. Heterostructure, which consist of substrate and two epitaxial layers with doped areas

Figure 2. Appearance from side of heterostructure from Fig. 1
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\[ \frac{\partial C_j(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x} \left[ D_{C_j} \frac{\partial C_j(x,y,z,t)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D_{C_j} \frac{\partial C_j(x,y,z,t)}{\partial y} \right] + \frac{\partial}{\partial z} \left[ D_{C_j} \frac{\partial C_j(x,y,z,t)}{\partial z} \right] \]  

(1)

with boundary and initial conditions

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

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

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

\[ C_j(x,y,z,0) = f_{C_j}(x,y,z). \]  

(2)

Here \( C_j(x,y,z,t) \) is the spatiotemporal distribution of concentration of dopant with number \( j \) (the first or the second); \( D_{C_j} \) is the diffusion coefficient of dopant with number \( j \). Value of dopant diffusion coefficient depends on properties of materials of layers of heterostructure, speed of heating and cooling of heterostructure (with account Arrhenius low). Redistribution of dopant is also depends on level of doping. Dependences of dopant diffusion coefficients on parameters could be approximated by the following function [8]

\[ D_{C_j} = D_{L_j}(x,y,z,T) \left[ 1 + \sum_{i=1}^{\gamma} C_j(x,y,z,T) \right] \]  

(3)

where \( D_{L_j}(x,y,z,T) \) is the spatial (due to inhomogeneity of heterostructure) and temperature (due to Arrhenius low) dependences of diffusion coefficient of dopant with number \( j \); \( P_j^r(x,y,z,T) \) is the limit of solubility of dopant with number \( j \); parameter \( \gamma \) depends on properties of materials and could be integer in the interval \( \gamma \in [1,3] \) [8]. The parameter \( \gamma \) coincides with average electrical charge of defects, which interacting with atoms of dopant [8].

Let us determine spatiotemporal distributions of dopants by using method of averaging of function corrections (see, for example, [17] and appropriate references in this paper) with decreased quantity of iteration steps [18]. Framework the approach we consider distribution of dopant concentration with averaged dopant diffusion coefficient \( D_{0L_j}(x,T) \) as the first-order approximation of solution of Eq.(1). The first-order approximation could be written as

\[ C_{j1}(x,y,z,t) = \frac{2\pi}{L_x L_y L_z} \sum_{n=1}^{\infty} F_{nc_j} c_n(x) c_n(y) c_n(z) e_{nc_j}(t) \]

where \( F_{nc_j} = \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} c_n(u) c_n(v) c_n(w) f_{C_j}(u,v,w) du dv dw; \) \( c_n(s) = \cos(\pi s/L_s); \)

\[ e_{nc_j}(t) = \exp \left[ -\pi^2 n^2 D_{0L_j}(1/L_x^2 + 1/L_y^2 + 1/L_z^2) \right] \]

We determine the second-order approximation and the approximation with higher orders of dopant concentration by using standard iteration procedure of method of averaging of function correction [17,18]. Framework the procedure to determine the approximation of dopant concentration with order \( n \) we shall replace the unknown distribution of concentration \( C_j(x,y,z,t) \) in the right side of Eq.(1) on the sum of the average value of the approximation with order \( n \) and approximation with the
previous order, i.e. \( \alpha_{nC_j} + C_{j,n-1}(x, y, z, t) \). The replacement gives us possibility to obtain equation for the second-order approximation of dopant concentration

\[
\frac{\partial C_{j2}(x, y, z, t)}{\partial t} = \frac{\partial}{\partial x} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial x} \right) + \\
+ \frac{\partial}{\partial y} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial y} \right) + \\
+ \frac{\partial}{\partial z} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial z} \right)
\]

(4)

Integration of left and right sides of Eq. (6) gives us possibility to obtain the second-order approximation of dopants concentrations in the following form

\[
C_{j2}(x, y, z, t) = \frac{\partial}{\partial x} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial x} d\tau \right) + \\
+ \frac{\partial}{\partial y} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial y} d\tau \right) + \\
+ \frac{\partial}{\partial z} \left( D_{L_j}(x, y, z, T) \prod_{i=1}^{j} \left[ 1 + \xi_j \left[ \frac{a_{2C_j} + C_{il}(x, y, z, t)}{P'_i(x, y, z, T)} \right] \right] \frac{\partial C_{j1}(x, y, z, t)}{\partial z} d\tau \right) + f_{C_j}(x, y, z)
\]

(4a)

The average value of the second-order approximation could be determine by standard relation [17,18]

\[
\alpha_{2C_j} = \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta L_x L_y L_z} \int_0^{\Theta L_x L_y L_z} \int_0^{\Theta L_x L_y L_z} \left[ C_{j2}(x, y, z, t) - C_{j1}(x, y, z, t) \right] d\tau dy dz d\tau 
\]

(5)

Substitution of the Eq. (4a) into Eq. (5) gives us possibility to obtain relation for the required average value \( \alpha_{2C_j} \)

\[
\alpha_{2C_j} = \frac{1}{L_x L_y L_z} \int_0^{L_x L_y L_z} \int_0^{L_x L_y L_z} \int_0^{L_x L_y L_z} f_{C_j}(x, y, z) d\tau dy dz d\tau 
\]

(6)

Analysis of the spatiotemporal distributions of concentrations of dopants has been done analytically by using the second-order approximation of the concentrations frame-work the method of averaging of function corrections with decreased quantity of iteration steps. The second-order approximation is usually enough good approximation to make qualitative analysis and to obtain some quantitative results. Results of analytical calculations have been checked by comparison with results of numerical simulation.
3. Discussion

Based on the results obtained in previous sections, we analyzed the dynamics of redistribution of dopants in a semiconductor heterostructure. Typical distributions of dopants at fixed values of the annealing time and different values of the difference between dopant diffusion coefficients in different layers of the heterostructure are presented in Fig. 3. The figure shows that the interface between layers of the heterostructure gives us the possibility to manufacture field-effect transistors with smaller dimensions in the direction of the source-drain and into another direction. The introduced ejection of the gate from the source-drain line gives us the possibility to decrease the dimensions of the transistor in this direction and depthward of the heterostructure. However, the dimensions of the transistor in the direction perpendicular to the source-drain line in the plane of the epitaxial layers increase. In this situation, one can obtain field-effect transistors with smaller thickness.

![Figure 3](image)

**Figure 3.** Distributions of dopants in a heterostructure with two layers for different values of the difference between values of diffusion coefficients. Increasing of number of curve corresponds to increasing of difference between values of diffusion coefficients.

Let us optimize the annealing time to maximize the effectiveness of annealing of dopant. If the annealing time is large, the distribution of dopant becomes more homogeneous. At the same time, the sharpness of the p-n-junction decreases. If the annealing time is small, the distribution of dopant becomes more inhomogeneous. Let us determine the optimal annealing time framework recently introduced criterion [14-16, 18]. Frameworks the criterion we determine the real distribution of dopant by idealized stepwise one (curve 1 of Fig. 4) and minimize the following mean-squared error:

\[
U = \frac{1}{L_1 L_2 L_3} \iiint_{0,0,0} \left[ C(x,y,z,\Theta) - \psi(x,y,z) \right] \, dz \, dy \, dx
\]

(7)

![Figure 4](image)

**Figure 4.** Spatial distributions of dopant in a heterostructure for diffusion doping. Curve 1 is an idealized distribution of dopant. Curves 2-4 are real distributions of dopant for different values of annealing time (increasing of number of curves corresponds to increasing of value of annealing time).

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\]

(7)

**Figure 5.** Dependences of dimensionless optimal annealing time, which have been calculated by minimizing the mean squared error Eq. (6) on several parameters. Curve 1 is the dependence of optimal annealing time on the ratio \(a_1/L_x\) (dependence of optimal annealing time on the ratio \(a_2/L_x\) is the similar to the dependence on \(a_1/L_x\)) for pairwise equality of dopant diffusion coefficients and \(\xi = \gamma = 0\), \(D_1/D_S = 1\). Curve 2 is the dependence of optimal annealing time on the relation \(D_1/D_2\) (dependence of optimal annealing time on the ratio \(D_2/D_3\) is the similar to the dependence on \(D_1/D_3\)) where \(D_i\) are the dopant diffusion coefficients in the epitaxial layers, \(D_S\) is the dopant diffusion coefficient in the substrate) for \(a_1/L_x = 1/2\), \(\xi = \gamma = 0\).

Curve 3 is the dependence of optimal annealing time on the parameter \(\xi\) for pairwise equality of dopant diffusion coefficients and \(a_1/L_x = 1/2\), \(\gamma = 0\), \(D_1/D_3 = 1\). Curve 4 is the dependence of optimal annealing time on the parameter \(\gamma\) for pairwise equality of dopant diffusion coefficients and \(a_1/L_x = 1/2\), \(\xi = 0\), \(D_1/D_3 = 1\).

Where \(\psi(x,y,z)\) is the approximation function (curve 1 of Fig. 4). Dependences of optimal annealing time on several parameters are presented on Fig. 5. Optimal annealing time increases with increasing of thickness of epitaxial layers, because one can find increasing time of dopant diffusion through the epitaxial layers. Optimal annealing time decreases with increasing of the relation \(D_1/D_S\) with fixed their average value. In this situation increasing of value of dopant diffusion coefficient leads to acceleration of dopant diffusion in epitaxial layer. Increasing of parameter \(\xi\) leads to increasing of influence of concentration dependence of dopant diffusion coefficient on diffusion process. In this situation, one can obtain increasing of dopant diffusion.
coefficient and acceleration of dopant diffusion. Increasing of value of parameter $\gamma$ leads to decreasing of influence of concentrational dependence of dopant diffusion coefficient on diffusion process, because dopant concentration is smaller, then limit of solubility of dopant. In this situation raising of the relation $C(x,y,z,t)/P(x,y,z,t)$ into the power $\gamma$ decreases.

4. Conclusion

In this paper we introduce an approach to fabricate a field-effect transistor, which gives us possibility to decrease dimensions of the transistor in two directions and increase dimension of the transistor in the third one. However the increasing of dimensions did not compensate decreasing of full volume of the transistor. The approach based on changing of configuration of transistor, manufacturing of transistor in inhomogenous structure (for example, in heterostructure) and optimization of annealing time of infused dopants for production of the transistor.

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