Optimisation and Problems of the Channel Area Formed by Two Ion Implantations in NMOS Structures

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Introduction

Formation of MOS transistor structures consists of many different technological operations (TO). TO depend on one another. Dependency can usually be identified by impurity redistribution n+1 TO. In the design phase it is crucial to select and determine the most accurate parameters of all TOs. Correct TO modes ensure lower percentage of manufacturing defects and faster choice of TO modes in the manufacturing process.

Optimization of the technological process in accordance with all TO parameters (factors) x, to ensure the selected MOS transistor structure’s parameters y, is very complex due to a high variety of factors x.

Manufacturing process simulation is performed on the Athena software package. Regression coefficients bn are calculated at the optimal values x and the optimal factor values xopt are presented at the set values of yopt.

Technology

The selected NMOS structure which technological route of manufacture consists of 23 main TOs (diffusion, implantation, etching etc.). Sketch of the structure is presented in Fig. 1. The analysed transistor is NMOS with the polysilicon gate, the width of which must match the channel length L = 90 nm [2,3].

In this case, the NMOS structure is formed on the 100 crystallographic orientation Si plate. After the preparatory TOs, the gate is formed on the basis of polysilicon [4]. After this TO, n− impurities are introduced, in this case phosphorus (P), by the use of ion implantation. The main modes of this II are the implantation dose and energy. The dose of this TO in the optimization equation is a factor x2, and energy is a factor x1. During the P implantation (for the n− field formation) the ion dose ranges between 1013 cm−2 and 1014 cm−2, and the energy from 1 keV to 50 keV. Then "spacer" oxide is formed, which will enable local doping of the source and drain areas n+ [1, 3, 5]. The dose of this TO in the optimization equation is a factor x3, and energy is a factor x1. During the implantation...
of arsenic (As) (for the $n^+$ area formation) the ion dose ranges between $10^{13}$cm$^{-2}$ and $10^{14}$cm$^{-2}$, and the energy from 1 keV to 50 keV. All of the TO (factor) parameters have an impact on the output parameter $y$, which in this case is the channel length $L$. Parameters of these TOs and their selection during the manufacture will depend on the set output parameters $y$ [4].

**Factor optimization algorithm**

MOS transistor simulation which is usually carried out at the design stage, is crucial to the quality parameters. In the production of NMOS the aim is to obtain the minimum channel in $L$, the minimum overlap $ΔL$, the optimal channel width $B$, the set output characteristic $U_{DS}=f(I_D)$ and transconductance $S$. All these desired parameters can be attributed to the optimization function’s output parameters $y_1, y_2, ..., y_n$. Meanwhile, there are more than one input parameters in the same manufacturing phase. These are the TO parameters – TO modes, II energy, II dose, and so on. These are the input parameters or factors $x_1, x_2, ..., x_n$.

The optimization model is described as the incomplete square polynomial (1) [2]

$$
\hat{y} = b_0 + \sum_{i=1}^{c_1} b_i x_i + \sum_{i=1}^{c_2} b_i^2 x_i^2 + \sum_{i=1}^{c_3} b_i^3 x_i^3 \ldots \ldots (1)
$$

To find the optimal values of the optimal $x$ managed factors it is common practice to use the extremal experiment (search for extremes) [2]. For this, we firstly prepare an adequate model.

![Cross-sectional diagram of the NMOS transistor with lateral impurity implantation.](image)

**Fig. 2.** Cross-sectional diagram of the NMOS transistor with lateral impurity implantation. When the TO parameters of phosphor ion implantation – energy 5 keV, dose $5\times10^{13}$ cm$^{-2}$, As – energy 5 keV, dose $5\times10^{14}$ cm$^{-2}$

Controlled factors will be the main TO modes of the P II – energy and dose, the main TO modes of the As II – energy and dose. As described above, these factors will correspond the factors $x_1, x_2, x_3, x_4$. So we will have the 4 factor plan, and tests $N=2^4$. As an output parameter, we accept the channel length $L$. In this case, look for the optimal values of $x$ at which $y=\hat{y}_{opt}$.

Typically by applying the extremal multifactor optimums search method, values $x_{opt}$ are found at which $y=\hat{y}_{min}$ or $\hat{y}=\hat{y}_{min}$ [2].

From the earlier tests we know that at the maximum dose, the value channel $L$ is destroyed when the II energy exceeds 10 keV, so we will set the range of changes and choose the initial factor values. Initial values of factors are assumed $x_1=5$ keV, $x_2=5\times10^{13}$ cm$^{-2}$, $x_3=5$ keV, $x_4=5\times10^{14}$ cm$^{-2}$. NMOS structure with the initial values of factors is presented in Fig. 2. The plan of 16 tests is prepared, where the step of edge values for energy is $\pm 0.1$ keV, and for the dose $P$ is $\pm 0.1\times10^{13}$ cm$^{-2}$, for the As dose $\pm 0.1\times10^{15}$ cm$^{-2}$.

Thus, the proposed algorithm based on which the optimum search steps in the design of the NMOS might be as follows:

1) Selection of the initial simulation parameter (factor) $x_i$ values;
2) The model for the search of the optimum is described as the polynomial (1);
3) The experimental plan is drafted (it can be a full factorial experiment method). The least number of tests to be carried out is $N=2^4$. In this case $n=4$. The step of changing the plan factors $Δλ$ is selected;
4) According to the selected plan, by using the existing Athena simulation software, we model the $y$ output values;
5) We check the adequacy of the optimum search model;
6) The equation regression coefficients $b_i$ are calculated;
7) According to the mathematical expression (2) we calculate the values of the new factors $x_{i,k+1}$

$$
x_{i,k+1} = x_{i,k} + \lambda bi;
$$

8) We perform steps 1-7 in the new factor space point;
9) We repeat steps 1-8 until the optimum search model becomes inadequate;
10) We check the obtained $y_{opt}$ and $x_{opt}$ according to the condition (3, 4, 5) and identify the position of values of the identified optimal factors by searching the true $X_{opt}$ at which $y$ is equal to the output parameter we want to obtain, with the given allowable tolerance $\varepsilon$. In the analysed case, the channel length $L'$

$$
y_{opt} > L' + \varepsilon \rightarrow x_{i,max}, \quad y_{opt} < L' - \varepsilon \rightarrow x_{i,min}, \quad y_{opt} = L' \pm \varepsilon \rightarrow x_{i,opt};
$$

11) If $y_{opt}=L' \pm \varepsilon$ then the optimum search is considered to be terminated. But if not, then we select the step $A$ of changing the initial factor values $x$ in the factor field $x_{imin} \leq x \leq x_{imax}$. It is recommended that the $A$ value is the same as $\lambda$ or less if necessary. We continue repeating steps 1-11 until the condition (3, 4, 5) is satisfied.

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Certainly one has to compare whether in the optimum point $h_j=0$ and the condition (6) must be satisfied

$$\sum_{j=1}^n h_j \leq \varepsilon.$$  \hspace{1cm} (6)

### NMOS structure optimization results

According to the selected NMOS technology and prepared 4 factor optimization algorithm we found the optimal values of TO factors $x_{i\text{opt}}$, $x_{2\text{opt}}$, $x_{3\text{opt}}$, $x_{4\text{opt}}$ for II. At these values, the optimisation function output $y_{\text{opt}}$ is close to the set $L'$.

It should be noted that this optimisation is important to apply in the design stage. Certainly, it is necessary to evaluate the parameters of all stages to the analysed output parameter of their group in manufacture. In this case, the area of optimisation factors is defined only with the TO parameters of As and P II. Other factors existing in the NMOS manufacture constant, therefore it is not possible to state that a complete optimisation of the full structure formation has been carried out.

![Fig. 3. Area of values of the $y$ output parameter obtained during simulations according to the prepared plan: 1 – area of output values is closest to the set $L'; 2$ – the bottom part of the area of output values](image)

This, in the analysed case, the set $\varepsilon = 1.0$ nm. The part of the area of output parameter values carried out according to the algorithm 1-11 steps is presented in Fig. 3. In this case, according to step 10 we determined the maximum and minimum values of factors and then determined the field of factors $x_i$ Fig. 4. As we see, for both impurities, the II energy area is established - $5 \leq x_1, x_3 \leq 6$ keV, dose area for P - $5 \times 10^{13} \leq x_2 \leq 6 \times 10^{13}$ cm$^{-2}$, dose area for As area - $5 \times 10^{14} \leq x_2 \leq 5 \times 10^{14}$ cm$^{-2}$. Next, the average parameter values from the defined area TO (II) were verified which indicated the further optimization direction. From the defined and obtained results we can determine (to make a hypothesis on) the direction of change of the NMOS channel length $L$ or any searched parameter $y$. In this particular case of the NMOS structure it has been determined that $y$ approaches the set $y=L' \pm \varepsilon$ nm when energy parameters (factors) for both implantations will change in the $5 \leq x_1, x_3 \leq 5.5$ keV value field, P II dose will change in the $5 \times 10^{13} \leq x_2 \leq 5 \times 10^{13}$ cm$^2$ value field, and As II dose will change in the $5 \times 10^{14} \leq x_2 \leq 5 \times 10^{14}$ cm$^2$ value field.

![Fig. 4. $x_i$ field of values according to the prepared factor change plan (step 3 of the algorithm)](image)

Thus, according to the proposed algorithm and after the verification of additional conditions (5, 6) the optimal factors $x_i$ values are determined. Accordingly, in this particular NMOS case the resulting $x_1=3.3$ keV, $x_2=5.18 \times 10^{13}$ cm$^2$, $x_3=5.05$ keV, $x_4=5.3 \times 10^{14}$ keV. Received $y_{\text{opt}}=91$ nm. NMOS structure according to the $x_{i\text{opt}}$ values is presented in Fig. 5.

![Fig. 5. Simulated NMOS structure at optimal $x_{i\text{opt}}$ values. P ("pocket" formation) ion implantation energy 3.30 keV, dose $5.18 \times 10^{13}$ cm$^2$; As ion implantation energy 5.05 keV, dose 5.30 cm$^2$](image)

At such TO parameters of such NMOS source and drain area formation, the obtained channel length $L$ does not ensure, however, brings closer to the optimum NMOS transistor output parameters. As seen in Fig. 5, we succeeded in $L$ optimisation and proposing an algorithm, but did not succeed mathematically to ensure the designed $pn$ junction depth. Therefore considerable attention was focused on the orthogonal deviation $\Delta R_p$ of the ion stretch, rather than the ion penetration depth $R_{p1}$ and $R_{p2}$ of separate TOs. We can state that the proposed optimisation algorithm does not ensure the set, and simultaneously the optimal NMOS output parameters, that are dependent from $R_{p1}$ and $R_{p2}$.
Conclusions

1. The NMOS transistor structure selected for the channel area optimisation allowing the implementation of the structures with the channel length of 90 nm. The source and drain areas of the structure, and simultaneously the channel is formed by two ion implantation TOs.

2. For the optimization of the n⁻ and n⁺ area formation TO parameter values, the 11 step and 3 cycle algorithm was proposed.

3. The optimisation of factor (TO parameter) values according to the desired (designated) output parameter (channel length) can be applied for the chosen technology.

4. The proposed algorithm assesses the 4 factor xᵢ mutual interaction effect on one output parameter y, therefore this algorithm can not be applied to the optimization of the complete NMOS manufacturing where x>4, and even more so when y>2.

5. After performing the optimization of the selected technology NMOS structure we obtained the following optimal TO parameter values of ion implantation – P ion implantation energy 3.30 keV, dose 5.18x10¹³ cm⁻²; As ion implantation energy 5.05 keV, dose 5.30 cm⁻².

6. The NMOS model, according to the received optimization results, showed that in the manufacture of nano-structures it is not enough to optimize factors according to a single given output value y because when changing the input parameters, other parameters of structures output are changing (pn junction depth, parasitic capacities etc.).

References


NMOS nano-structure channel structure depends on a number of technological processes. It is important to find and evaluate depend of technological operations (TO) parameters to NMOP structures and output caharacteristics. The number of TOs in fabrication process is big, therefore it is difficult to evaluate and carry out optimization of all factors xᵢ (TO parameters). Wherefore proposed optimization algorithm of 4 factors xᵢ (energy and dose of to ion implantations parameters) by set output parameter value y(L) with the given allowable tolerance ε. This model is applicable for NMOS structures with designed 90 nm channel. III. 5, bibl. 9 (in English; abstracts in English, Russian and Lithuanian).


Visų NMOP nanostrukūrų kanalo sritis priklauso nuo daugelio technologinių procesų. Projeckavimo NMOP vėliau omenyti parameetrams technologinių operacijų (TO) įtaką NMOP struktūros stėgėms ir yra išimkamos atvirkščios priklausomybės. Nuo technologinių procesų atsakingų yra energija ir dėsės, o dalis ispanacių TÖ parameterų yra susijusios su įvairiomis spektrometris. Todėl gali būti prisiminti, kad įvairios NMOP nanostrukūros atlieka 90 nm ilgio kanalo formavimą. III. 5, bibl. 9 (angliškai; pranešimai įmonių, rusų ir lietuvių kalbomis.)

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