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MODEL OF SIMULATION OF THE PROCESS OF FORMATION OF FUNCTIONAL SURFACES OF MICRO-OPTO-ELECTRO-MECHANICAL SYSTEMS' COMPONENTS

The subject of the article is to establish the relationships between the parameters of formation the functional surfaces of the substrates of micro-opto-electro-mechanical systems' (MOEMS) components and their physical and technological parameters. Objectives: to increase the reliability and reproducibility of the received information, reduce the complexity of the technological process of forming, by modeling the dependences of the ratios of physical and technological parameters of forming the functional surfaces of the substrates of MOEMS components for the forming process. The methods are used: methods of experiment planning and computer processing of experimental data, mathematical models, digital computer modeling of technological processes. The following results were obtained: a mathematical model was proposed, which was used to model the influence of physical and technological parameters of the functional surfaces of the substrates of MOEMS components on their formation, with the receipt of prototypes. The results can be used in the development of technological processes of production, as substrates of functional components of MOEMS, and other functional elements for various technological purposes. A mathematical model is obtained, which allows predicting the degree of influence of physical and technological parameters of the technological process on the parameters of formation of functional surfaces of substrates of MOEMS components. Conclusions. The scientific novelty of the results is as follows: a mathematical model that has found practical implementation for computer digital modeling in the development of technological processes for the production of functional surfaces of substrates of MOEMS components is proposed, in which, unlike the existing ones, it is possible to predict the degree of influence of physical substrates of MOEMS components, which allows to plan the process of formation, increase the reproducibility of results and reduce the complexity of the technological process.

Keywords: *micro-opto-electro-mechanical systems', functional component, shaping, physical and technological parameters, mathematical model, modeling, abrasive processing, grinding, polishing.*

Introduction

One of the many most common types of microelectromechanical systems (MEMSs) are micro–optical electromechanical systems (MOEMSs) [1].

These are microchips with functional components. The ability to perform complex operations with a light beam (reflection, diffraction, modulation, spatial orientation, redirection) is possible through the use of miniature functional elements and is one of the main advantages of MOEMS [1].

The performance of such transmission systems depends on the quality of the components used. The necessary parameters can be guaranteed only if the technological process of their production is strictly adhered to and the use of high–precision equipment for control and data processing [2–4], which can be predicted by the results of digital computer modeling.

One of the most important operations in the production process of MOEMS components is molding [5].

Finishing operations in this technological process – grinding and polishing the surface of the substrate of functional components.

The need for grinding and polishing is due to the fact that at almost every stage of the manufacturing process of the plate on the surface of the substrates of MOEMS components remain scratches, chips, cracks, swelling, oxidation and other defects that lead to heterogeneity of the surface layer of substrates and changes in its physical and technological parameters: such a layer is called broken. To remove it, the surface of the plate of the MOEMS component is ground, etched and polished [5–9].

This work is devoted to the study of parameters and factors that directly affect the formation of functional components of MOEMS in finishing operations and the development of a mathematical model that predicts the degree of influence of physical and technological parameters of the process on the formation of functional surfaces of MOEMS components.

The surface roughness of the functional component is the main indicator of shaping, which is critical at each stage of manufacturing such components [6].

Statement of basic materials

At the first stage, using experimental planning theories, a multifactorial experiment was selected and factorial planning was performed.

At the second stage, a mathematical model was developed, which presents experimental modeling data.

A full factorial experiment was conducted to provide prediction and control of technological processes of formation of substrates of functional components of MOEMS during polishing and grinding with different types of diamond grinding pastes (ACM 2/1, ACM1 4/10, ACM 0/28) and gave recommendations for the formation of physical–technological parameters of the technological process of forming such components.

At the third stage, the authors presented samples of the components of the functional substrates of MOEMS' components, obtained by the proposed modeling as a result of the experimental technological process of production using the recommendations.

Experiment planning.

To model the influence of the modes of finishing technological operations on the parameters of the formation of the substrates of the functional components of MOEMS, the authors used a complete factorial experiment [10].

To perform the experiment, the following should be done:

– to obtain and to analyze a priori information;

– to select input and output variables;

– to develop a mathematical model according to which experimental data will be presented;

– to determine the method of data analysis;

– to conduct an experiment;

– to check the statistical preconditions for the obtained experimental data;

– to process the results and interpret them, as well as to develop recommendations for the selection of parameter values [10];

– to obtain the planned values of the parameters of processing operations in the formation of the substrates of the MOEMS component.

Selection of factors and their intervals of variation.

As is known [3–6; 11–18], the most significant input factors of finishing technological operations of molding, meeting all the requirements of the factorial experiment, are the processing time of the sample – $t\ (min)$, spindle speed – $v\ (rpm)$ and grain size of the polishing and grinding pastes – $z\ (\mu m)$.

It should be noted that the choice of factors did not take into account one of the important parameters – the pressure of the polishing tool, which acts on the sample.

In all the experiments conducted, the pressure was constant and of the same value.

Limits of change of factors: the maximum time of processing of material within $t_{max} = 20\ min$, and $t_{min} = 10\ min$; disk rotation speed – $v_{max} = 40\ rpm$, $v_{min} = 30\ rpm$; the grain size of the paste is $z_{max} = 32\ \mu m$, $z_{min} = 2\ \mu m$. Variant factors are listed in table 1.

Table 1

Limits of change and design of factors

Factors	Processing time (min)	Disk rotation speed (rpm)	Graininess of pastes (μm)	Roughness (μm)
Accepted designation	t	v	z	Ra
Designation in MFE	x_1	x_2	x_3	Y
Upper limit (1)	*20*	*40*	*32*	–
Basic level (0)	*15*	*35*	*17*	–
Lower limit (–1)	*10*	*30*	*2*	–

Experiment planning is preceded by the stage of determining the center of the experiment and the intervals of variation of factors.

At the same time, the boundaries of the areas for determining factors set by technical restrictions are estimated [10].

Based on the research [11–16], we choose the factors on which the resulting value of the roughness of the material $Y(\mu m)$ depends [10].

Let's make the generalized formula of dependence:

$$Y = f(t, v, z), \quad (1)$$

where t, v, z – factors influencing the value Y. Let's construct a matrix of a complete factorial experiment, and list the results in table 2.

Since the true form of the basic function (2) is unknown, we will use the equation representing the decomposition of this function into a series to describe the response surface [10]:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{ij=1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2, \quad (2)$$

where x_i, x_j – variables at $1 \ldots n,\ j = 1 \ldots n,\ i \neq j$;

$b_0,\ b_i,\ b_{ij}$ – regression coefficients for the corresponding variables, the values of which determinethe shape of the response surface.

Table 2

The results of a complete factorial experiment

№	t	v	h	x_1	x_2	x_3	$x_1 \times x_2$	$x_1 \times x_3$	$x_2 \times x_3$	$x_1 \times x_2 \times x_3$	$x_{11} = x_1^2 - d$	$x_{22} = x_2^2 - d$	$x_{33} = x^2 - d$	y
1.	20	40	32	1	1	1	1	1	1	1	0,2697	0,2697	0,2697	44,1
2.	10	40	32	–1	1	1	–1	–1	1	–1	0,2697	0,2697	0,2697	20,6
3.	20	30	32	1	–1	1	–1	1	–1	–1	0,2697	0,2697	0,2697	35,7
4.	10	30	32	–1	–1	1	1	–1	–1	1	0,2697	0,2697	0,2697	17,9
5.	20	40	2	1	1	–1	1	–1	–1	–1	0,2697	0,2697	0,2697	12,2
6.	10	40	2	–1	1	–1	–1	1	–1	1	0,2697	0,2697	0,2697	5,8
7.	20	30	2	1	–1	–1	–1	–1	1	1	0,2697	0,2697	0,2697	9,7
8.	10	30	2	–1	–1	–1	1	1	1	–1	0,2697	0,2697	0,2697	4,5
9.	24,308	35	17	1,2154	0	0	0	0	0	0	0,7469	–0,7303	–0,7303	28,4
10.	7,846	35	17	–1,2154	0	0	0	0	0	0	0,7469	–0,7303	–0,7303	8,1
11.	15	48,616	17	0	1,2154	0	0	0	0	0	–0,7303	0,7469	–0,7303	30,2
12.	15	23,538	17	0	–1,2154	0	0	0	0	0	–0,7303	0,7469	–0,7303	14,7
13.	15	35	38,8928	0	0	1,2154	0	0	0	0	–0,7303	–0,7303	0,7469	46,6
14.	15	35	1,5692	0	0	–1,2154	0	0	0	0	–0,7303	–0,7303	0,7469	3,8
15.	15	35	17	0	0	0	0	0	0	0	–0,7303	–0,7303	–0,7303	22,6

The calculated numerical values of the regression coefficients are listed in table 1.

Verification of the statistical significance of the parameters of the regression equation (regression coefficients) was performed by Student's *t*–test [5; 10].

The reproducibility variance was determined [10]. The calculated numerical values of the variance of the coefficients of the regression equation are listed in table 3.

Table 3

Calculated numerical values of the variance of the coefficients of the regression equation

Regression coefficients	Verification of regression coefficients according to Student's criterion				
	Numerical value	$S_2 b_i$	tb_i	The tabular value of the Student’s coefficient	Significance check
b_0	20,33	0,418	31,456	1,886	Significant
b_1	5,17	0,572	6,839	1,886	Significant
b_2	2,25	0,572	2,975	1,886	Significant
b_3	9,21	0,572	12,177	1,886	Significant
b_{12}	0,46	0,783	0,520	1,886	Not significant
b_{13}	1,98	0,783	2,238	1,886	Significant
b_{23}	0,49	0,783	0,550	1,886	Not significant
b_{123}	0,30	0,783	0,339	1,886	Not significant
b_{11}	–1,22	1,435	1,016	1,886	Not significant
b_{22}	–0,39	1,435	0,325	1,886	Not significant
b_{33}	0,15	1,435	0,127	1,886	Not significant

Regression equation (3) in coded form has the following meaning:

$$y = 20,33 - 5,17x_1 + 2,25x_2 + 9,21x_3 + 1,98x_{13}. \quad (3)$$

To assess the adequacy of the model, it was evaluated according to Fisher's test. Let’s find the coded calculated values according to the obtained regression equation. The results of the coded calculated experimental values of the response of the function are listed in table 4.

Table 4

The results of coded calculated experimental values of the response function

No. of experiment	$\bar{y}_u$, μm	$\bar{y}_u$, μm
1.	44,1	38,9
2.	20,6	24,6
3.	35,7	34,4
4.	17,9	20,1
5.	12,2	16,6
6.	5,8	10,2
7.	9,7	12,1
8.	4,5	5,7
9.	28,4	36,6
10.	8,1	14
11.	30,2	23,1
12.	14,7	17,6
13.	46,6	31,5
14.	3,8	9,1
15.	22,6	20,3

Determining the degree of influence of factors on the formation of the MOEMS component.

To obtain the response surface, each of the three factors was recorded at zero level: t = 15 *min*, v = 35 *rpm*, z = 17 μ*m*.

Substituting these values, the regression equation was decoded, and three equations with two factors were obtained [10]. To decode equations (4–6), x_i was replaced by natural values:

$$x_1 = \frac{t-15}{5} = 0{,}2t - 3. \quad (4)$$

$$x_2 = \frac{v-35}{5} = 0{,}2v - 7. \quad (5)$$

$$x_3 = \frac{z-17}{15} = 0{,}057z - 1{,}13. \quad (6)$$

After decoding (formula 7) began to look like:

$$\begin{aligned} y(t,v,h) &= 20{,}33 + 5{,}17(0{,}2t-3) + 2{,}25(0{,}2v-7) + \\ &+ 9{,}21(0{,}05z-1{,}13) + 1{,}98(0{,}2-3)(0{,}005z-1{,}13). \end{aligned} \quad (7)$$

After performing transformations and reductions, we obtain the equation (8–11):

$$\begin{aligned} y(t,v,h) &= 0{,}58652 \times 15 + 0{,}45v + \\ &+ 0{,}1635z + 0{,}0198tz - 14{,}6251. \end{aligned} \quad (8)$$

$$y_{t=15}(v,z) = 0{,}45 \times v + 0{,}4605 \times z - 5{,}8273. \quad (9)$$

$$\begin{aligned} & y_{v=35}(t,z) = \\ & = 0{,}58652t + 0{,}1635z + 0{,}0198tz + 1{,}1249. \end{aligned} \quad (10)$$

$$y_{z=17}(t,v) = 0{,}92312 \times t + 0{,}45 \times v - 1{,}1249. \quad (11)$$

Using the proposed mathematical model, the results of modeling the influence of physical and technological parameters of the functional surfaces of the substrates of the components of MOEMS on their formation were obtained.

According to the obtained equations of the response surface, the dependence of material removal on the duration of processing, different grinding pastes, the results are presented in Figures 1 (two–dimensional version), 2 – 4 (three–dimensional version).

According to the obtained graphs, the influence of each factor (or combination of factors) of the technological process of grinding and polishing on the parameters of the formation of the functional surfaces of the substrates of the components of MOEMS was evaluated.

The magnitudes and combination of factors were determined to obtain the planned roughness of the test sample.

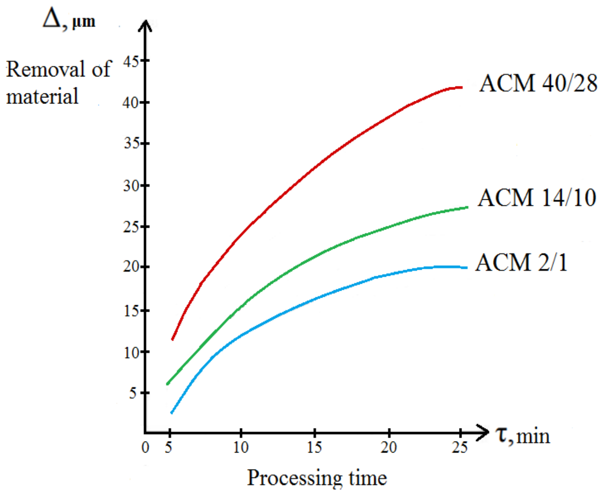


Fig. 1. Dependence of material removal on the processing time

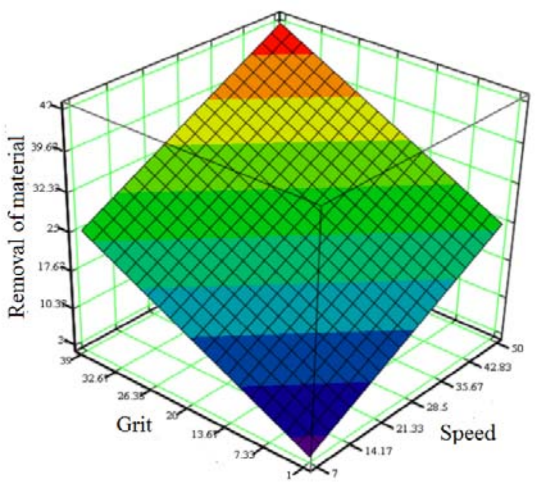


Fig. 2. Response surface at a fixed value of processing time

At the next stage, the authors obtained experimental samples of the components, using the results of computer modeling of the formation of the surfaces of the functional substrates of the micro-opto-electro-mechanical systems' components.

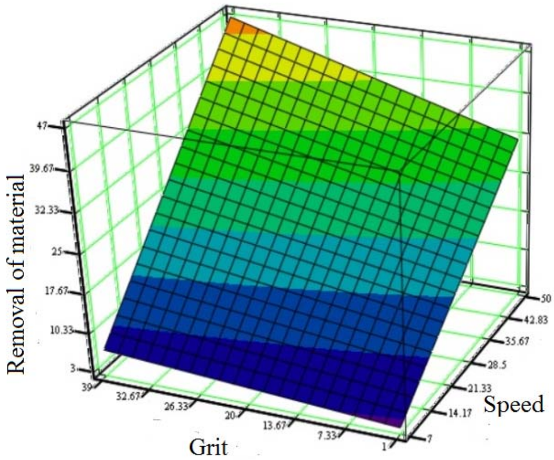


Fig. 3. Response surface at a fixed value of the spindle speed

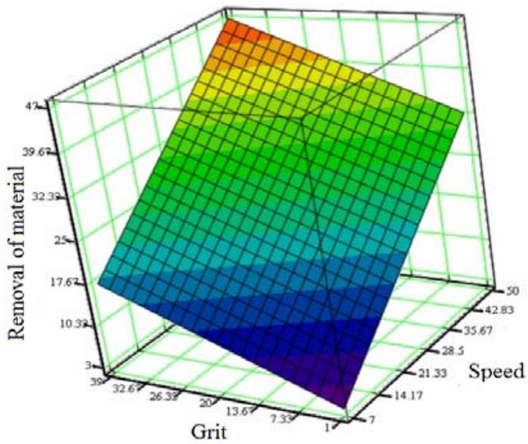


Fig. 4. Response surface at a fixed value of diamond paste grain size

Figure 5 shows the surface of the functional substrate of the MOEMS component made of silicon (5A–K processing), the response surface of which was formed in the mode at a fixed time value (5 b).

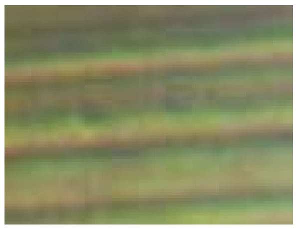
Figure 6 shows the surface of the functional substrate of the micro-opto-electro-mechanical systems' component of silicon (6 a – before processing) and the response surface at a fixed value of the spindle speed after processing (6 b), and Fig. 7 shows the surface of the functional substrate of the micro-opto-electro-mechanical systems' component of silicon (7 a – before processing) and the response surface at a fixed value of the grain size of diamond paste (7 b).

a

b

Fig. 5. The surface of the functional substrate of the MOEMS component made of silicon
a – before processing;
b – the response surface of which was formed in the mode at a fixed value of time

a

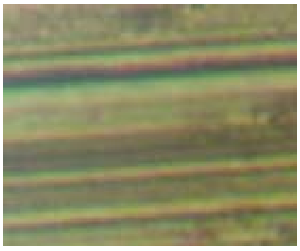


b

Fig. 6. The surface of the functional substrate of the MOEMS component of silicon
a – before processing;
b – the response surface at a fixed value of the spindle speed after processing

a

Fig. 7 The surface of the functional substrate of the MOEMS component of silicon
a – before processing



b

Fig. 7. The surface of the functional substrate of the MOEMS component of silicon
b – the response surface at a fixed value of the grain size of diamond paste

The next stage of the experiments, it is planned to use the method of computer modeling proposed by the authors [19] to control the functional surfaces of MOEMS components, using the interference control method. Using this method, it was possible to increase the reliability and reproducibility of the results of the technological process of production of functional surfaces of MOEMS components, to obtain the values of the graphically constructed “route” of the RMS values of the roughness of the functional surface component.

The obtained results in the complex should be used in the development of technological processes for the production of functional substrates of MOEMS components, to model the processes of molding and increase the accuracy of control of molding and reduce the complexity of the technological process as a whole.

It should be noted that in order to expand the research [20–23], the proposed mathematical model for modeling was used in the manufacturing process of a solar collector with a wedge concentrator [22] and a solar module with a stationary parabolocylindrical concentrator. [23], at the stage of the technological process of forming the substrates of the functional elements of these objects, the functional working surface of which is a mirror. Improving the design of devices [22–23], made it possible to increase their efficiency by increasing the luminous flux density by 2–4 times.

Conclusions

The influence of physical and technological parameters of the functional surfaces of the substrate of MOEMS components on their formation is modeled, with obtaining experimental samples of the substrates of MOEMS components.

The simulation results can be used in the development of technological processes of production, as the substrates of the functional elements of MOEMS, and the component as a whole.

A mathematical model that has found practical implementation for computer digital modeling in the development of technological processes for the production of functional surfaces of substrates of MOEMS components, in which, unlike existing ones, it is possible to predict the degree of influence of physical and technological parameters substrates of MOEMS components, which allows you to plan the process of formation, increase the reproducibility of results and reduce the complexity of the development of the technological process.

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МАТЕМАТИЧНА МОДЕЛЬ ДЛЯ МОДЕЛЮВАННЯ ПРОЦЕСУ ФОРМОУТВОРЕННЯ ФУНКЦІОНАЛЬНИХ ПОВЕРХОНЬ КОМПОНЕНТІВ МІКРО-ОПТО-ЕЛЕКТРО-МЕХАНІЧНИХ СИСТЕМ

І.Ш. Невлюдов, О.О. Чала, О.І. Филипенко, І.В. Боцман

Предметом *статті є встановлення залежностей між параметрами формоутворення функціональних поверхонь підкладин компонентів МОЕМС та їх фізико–технологічними параметрами* ***Завдання:*** *підвищення достовірності та відтворюваності отримуваної інформації, зниження трудомісткості технологічного процесу формоутворення, шляхом проведення моделювання залежностей співвідношень фізико–технологічних параметрів формоутворення функціональних поверхонь підкладин компонентів МОЕМС на процес формоутворення.* ***Методами*** *є: методи планування експерименту та комп'ютерної обробки експериментальних даних, математичні моделі, цифрове комп'ютерне моделювання технологічних процесів. Отримані такі* ***результати****: запропоновано математичну модель, яку застосовано для проведення моделювання впливу фізико–технологічних параметрів функціональних поверхонь підкладин компонентів МОЕМС на їх формоутворення, з отриманням дослідних зразків. Результати* ***можуть бути використані*** *при розробці технологічних процесів виробництва, як підкладин функціональних компонентів MOEMS, так і інших функціональних елементів різного технологічного призначення.* ***Отримано*** *математичну модель, яка дозволяє прогнозувати ступінь впливу фізико–технологічних параметрів технологічного процесу на параметри формоутворення функціональних поверхонь підкладин компонентів МОЕМС.* ***Висновки.*** *Наукова новизна отриманих результатів полягає в наступному. За-*

пропоновано математичну модель, що знайшла практичну реалізацію для комп'ютерного цифрового моделювання, при розробці технологічних процесів виробництва функціональних поверхонь підкладин компонентів МОЕМС, у якій на відміну від існуючих, є можливість прогнозування ступеню впливу фізико–технологічних параметрів технологічного процесу формоутворення на параметри формоутворення функціональних поверхонь підкладин компонентів МОЕМС, що дозволяє планувати процес формоутворення, підвищити відтворюваність результатів та знизити трудомісткість розробки технологічного процесу.

Ключові слова: *МОЕМС, функціональний компонент, формоутворення, фізико-технологічні параметри, математична модель, моделювання, абразивна обробка, шліфування, полірування.*

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ДЛЯ МОДЕЛИРОВАНИЯ ПРОЦЕССА ФОРМООБРАЗОВАНИЯ ФУНКЦИОНАЛЬНЫХ ПОВЕРХНОСТЕЙ КОМПОНЕНТОВ МИКРО-ОПТО-ЭЛЕКТРО-МЕХАНИЧЕСКИХ СИСТЕМ

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Аннотация. *Предметом статьи является установление зависимостей между параметрами формообразования функциональных поверхностей подложек компонентов МОЕМС и их физико–технологическими параметрами.* ***Задача****: повышение достоверности и воспроизводимости получаемой информации, снижение трудоемкости технологического процесса формообразования, путем проведения моделирования зависимостей соотношений физико–технологических параметров формообразования функциональных поверхностей подложек компонентов МОЕМС на процесс формообразования.* ***Методами являются****: методы планирования эксперимента и компьютерной обработки экспериментальных данных, математические модели, цифровое компьютерное моделирование технологических процессов.* ***Получены следующие результаты****: предложена математическая модель, которую применено для проведения моделирования влияния физико–технологических параметров функциональных поверхностей подложек компонентов МОЕМС на их формообразования, с получением опытных образцов. Результаты могут быть использованы при разработке технологических процессов производства, как подложек функциональных компонентов MOEMS, так и других функциональных элементов различного технологического назначения. Получена математическая модель, которая позволяет прогнозировать степень влияния физико–технологических параметров технологического процесса на параметры формообразования функциональных поверхностей подложек компонентов МОЕМС.* ***Выводы.*** *Научная новизна полученных результатов заключается в следующем. Предложена математическая модель, которая нашла практическую реализацию для компьютерного цифрового моделирования при разработке технологических процессов производства функциональных поверхностей подложек компонентов МОЕМС, которая в отличие от существующих, позволяет прогнозировать степень влияния физико–технологических параметров технологического процесса формообразования на параметры формообразования функциональных поверхностей подложек компонентов МОЕМС, что позволяет планировать процесс формообразования, повысить воспроизводимость результатов и снизить трудоемкость разработки технологического процесса.*

Ключевые слова: *МОЭМС, функциональный компонент, формообразования, физико-технологические параметры, математическая модель, моделирование, абразивная обработка, шлифовка, полировка.*