# Methodology for Variant and Generative Design of Microcomponents Based on the CAD System "MICROSYS 25"

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*Abstract*— **Microsystems engineering (MSE) is becoming increasingly important for the future technical and economic development of the world. The global market for microsystems products is experiencing tremendous growth, with countries such as the USA, Japan and Germany reaching high levels of development and technological development. It is currently a strategic direction that determines the development of human civilization and completely changes the appearance of manufactured products in the 21st century. Microengineering concerns technolo-gies and the practical implementation of three-dimensional structures and elements based on them with dimensions in the order of micrometers (μm). One of its main goals is to integrate microelectronic circuitry with micromechanical three-dimensional structures, by implementing complex integrated complexes called microsystems (MS). The purpose of this report is to present the developed methodology for variant and generative design of the specialized automated system for designing products from Microsystems Engineering "MICROSYS 25". The developed standard technolo-gical process for the production of flat circular membranes with double-sided plugs, by double-sided anisotropic etching, is illustrated. The recording of the generated information and a standard technological process in the relational database of an automated system is presented. The further development of the "MICROSYS 25" project is the development of multiple technological processes for micromechanical elements and components and their recording in the library database and thus optimizing the process of developing new technological processes.**

## I. INTRODUCTION

The specific characteristics of MSs compared to traditional (macrosystems - MS) are based mainly on their size [3]. When choosing a method for automated design of MSs, the methods of their production and operation are taken into account. Group technologies are usually used for the production of microsystems. When applying such technologies, a large number of elements are processed simultaneously, while manual intervention is not necessary or is insignificant. The production equipment used is expensive, since high accuracy requirements are imposed. It is economically advantageous to produce microsystems in large quantities. Microsystem technology is unsuitable for the production of prototypes, because the scheme of mass production using group technology is violated. Unlike traditional systems, the possibility of repair in microsystems is limited. Therefore, the main goal in development is to obtain a fully functioning system at the first implementation. The development of microsystems production is aimed at reducing the cost of materials and equipment, the number of technological operations and improving their functional properties (accuracy, operating range, sensitivity, etc.) while simultaneously increasing reliability. With the increasing complexity of microsystems, the design stage plays an increasingly important role in the production process. The developed automated system "MICROSYS 25" covers all stages of design – geometric modeling, engineering analysis and determination of a technological process for

manufacturing. The object of design is micromechanical functional elements, which are the smallest units of microsystems.

For the Automated Design (AD) of components and Technological Processes (TP) for them in the "MICROSYS 25" system, two main design approaches are used:

- Variant design;
- Generative design.

The algorithm for generative design is described in detail in "Algorithm and flowchart for geometric modeling of microcomponents based on the CAD system "MICROSYS 25"" [3]. The basis of variant design is the unification of components and functional elements and the basic technologies for their production. It is expressed through the use of TTP and group processing methods. Group technology is a production concept in which the existing similarities of the designed objects and TP are identified and used in order to obtain advantages in their design and production by uniting them in groups.

For the implementation of variant design of micromechanical functional elements, a classification and coding system has been developed, with components and functional elements (FE) divided into groups [3]. The criteria for separation are the similar constructive and technological features of FE, according to the sequence of their processing and the assignment of a given FE to a specific microcomponent (MC) – microsensor or executive micromechanism (microactuator).

The facet classification method was used, in which the set of components and FEs were divided into independent sets. Monocodes with a hierarchical tree structure were used for coding. The meaning of each position depends on the meaning of the previous position. This method of coding allows coding a large amount of information using a limited set of symbols and the ability to update the classifiers [1, 2].

The following classifiers were developed [3]:

- MC in electromechanical microsystems - microsensors and microactuators are systematized in detail.
- Micromechanical functional elements, divided into groups of beams, plates, membranes, pyramidal and V-shaped combs, blades, needle supports, 3D-partially movable microstructures, etc. The groups are subdivided into subgroups according to the geometric features of the FE.

Technological processes in microtechnology (MT) are divided into the following main groups:

- Methods for applying layers on a substrate or a previous layer [4];
- Methods for modifying and structuring the surface layer of the substrate [11];
- Structuring by micromachining;
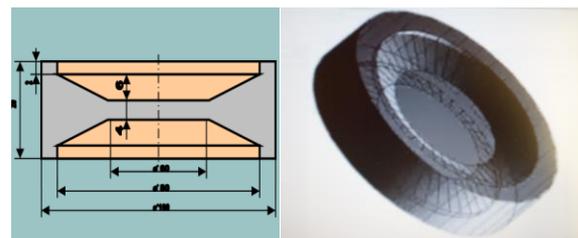- Radiation processing methods.

A classification [3] has been developed based on information about:

- MC – types, principle of operation, application;
- FE – design parameters, standard technologies for their production;
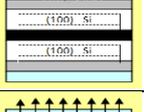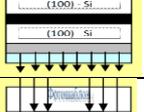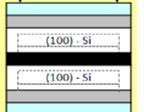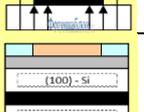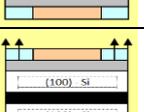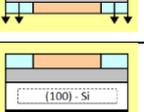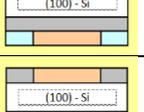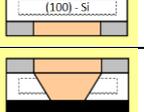- TP – principles of processes, schemes and parameters, equipment, application.

According to the block diagram of the algorithm for geometric design of micromechanical functional elements of the "MICROSYS 25" system, a ready-made geometric model corresponding to the designed functional element is searched from the database [3]. If such a model exists, only the specific geometric parameters and material are entered, then engineering analysis is performed. If a ready-made model does not exist, geometric modeling of FE is performed and its recording in the database as a ready-made model for subsequent design of other FEs with the same geometry is performed. After conducting the engineering analysis, technological design is performed. A standard technology for the production of the designed FE is searched in the database. When such a technology is found, it is edited, and technological documentation is output depending on the FE parameters. If there is no standard technology for the designed FE, we proceed to generative design.

For each group of functional elements, a common TP is developed, which is called the standard technology. Table 1. shows a standard technology for manufacturing round membranes with double-sided stoppers by anisotropic etching, with dimensions in μm and the membrane colored in gray.

TABLE 1 TYPICAL TECHNOLOGICAL PROCESS FOR MANUFACTURING FLAT CIRCULAR MEMBRANES WITH DOUBLE-SIDED STOPPERS BY DOUBLE-SIDED ANISOTROPIC ETCHING



| No. | Operation scheme | Operation code | Name of the operation |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1 | (100) - Si | | Preparing the substrate |
| 2 | p+  (100) - Si | 2.1.2.1  2.1.2.1.1  2.1.2.2.1 | Doping: Building an etch-stop layer by doping with the chemical element boron (B) 1. By general diffusion for sizes 1÷25 μm (for boron) 2. By general ion implantation – for sizes up to 1 μm (for boron) |
| 3 | (100) - Si  (100) - Si | 1.1.3  1.1.3.1  1.1.3.2  1.1.3.3 | Epitaxy: Building an epitaxial p-Si layer 1. Gas phase epitaxy for sizes 4÷17 μm 2. Solution epitaxy – for sizes 2.4μm 3. Molecular beam epitaxy – for |

| | | | sizes below 1 μm |
|---|---|---|---|
| 4 | [Силициев двуокис / (100) - Si / (100) - Si diagram] | 2.1.1<br>2.1.1.1<br>2.1.1.2 | Oxidation:<br>1. Liquid thermal oxidation<br>2. Dry thermal oxidation |
| 5 | [Силициев двуокис / (100) - Si / (100) - Si diagram] | 2.2.1<br>2.2.1.0.0.1 | Photolithography:<br>Surface preparation, washing and drying. |
| 6 | [Фоторезист / (100) - Si / (100) - Si diagram] | 2.2.1<br>2.2.1.0.0.2 | Photolithography:<br>Deposition of photoresist |
| 7 | [(100) - Si / (100) - Si diagram with arrows] | 2.2.1<br>2.2.1.0.0.3 | Photolithography:<br>Drying – removing the solvent and bringing the photoresist into a solid insoluble phase |
| 8 | [(100) - Si / (100) - Si diagram with arrows] | 2.2.1<br>2.2.1.0.0.4 | Photolithography:<br>Photopattern alignment (photo template) and exposure – the positive resist under the influence of light passes into an insoluble phase |
| 9 | [(100) - Si / (100) - Si diagram] | 2.2.1<br>2.2.1.0.0.5 | Photolithography:<br>Developing the photoresist – washing in solvent to remove the exposed resist |
| 10 | [(100) - Si / (100) - Si diagram with arrows] | 2.2.1<br>2.2.1.0.0.6 | Photolithography:<br>Fixing – hardening of the resist and removal of solvent residues |
| 11 | [(100) - Si / (100) - Si diagram] | 2.2.1<br>2.2.1.0.0.7 | Photolithography:<br>Local Etching – Through a Photoresist Mask<br>1. Liquid Local Etching<br>2. Dry Local Etching |
| 12 | [(100) - Si / (100) - Si diagram] | 2.2.1<br><br>2.2.1.0.0.8 | Photolithography:<br>Photoresist Removal – "Stripping"<br>1. In boiling $H_2SO_4$<br>2. Gas and ionic |
| 13 | [(100) - Si diagram] | 2.3<br>2.3.1<br><br>2.3.2. | Double-sided anisotropic etching<br>1. Liquid chemical anisotropic etching<br>2. Dry anisotropic etching |
| 1 | 2 | 3 | 4 |

## II. Materials and Methods

The automated system "MICROSYS" is for structural and technological design of MME. Its variant design algorithm has been tested using examples from the classifiers of components and technological processes for them. The database built on the basis of the classifiers allows "MICROSYS 25" to be used as an information - reference system or catalog system for the selection of functional MME, through its visualization modules [12, 13].

### Membrane fabrication

Membranes are most often produced from resist etched layers that are deposited and structured on a substrate before anisotropic deep etching. As such, mask layers made of SiC, $Si_3N_4$, $SiO_2$ or doped stop layers are used [11]. Membranes can be double-sidedly located on the substrate or attached layers to supports. Figure 4 shows a silicon oxynitride membrane, which is coated on the front, front side of the substrate by through-etching of the same on the reverse side. Therefore, as a rule, double-sided polished substrates are used, which are coated on the reverse side with a mask layer. The mask layer and the membrane layer can be made of the same material, so that the coating of the front and back sides in a CVD (chemical) reactor can be carried out in successive operations [14, 15]. The profile holes in the back mask layer determine the sagging and positioning of the membrane on the front side. The decisive parameter here is the thickness of the substrate and the deviations from it must be minimal. If the membrane must take the correct position relative to the movable structures on the front side, double-sided development is used in the structuring by lithography.

The production of the front side of the membrane is possible by etching, by obtaining an etched ridge. The membrane shown in Figure 1 (b) is suspended on four supports and is a basic structure for applying, for example, functional layers of a sensor, which must have good thermal insulation to the periphery. When designing the profile openings, the design rules (h>c) are observed.

The etching of closed membranes on the reverse side can be carried out in a single dose, with which the intended structures on the front side (e.g. metallization) are protected before the etching bath. In this way, On-Chip - the integration of microelectronic circuits with micromechanical membrane structures is achieved.
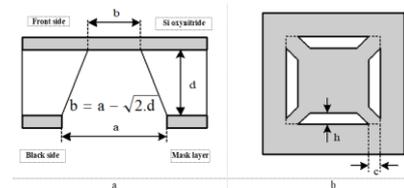
Fig. 1. Etching of membranes:

a) on the reverse side; b) on the front side, under etching condition h>c

The mechanical stresses in membrane-type structures are an essential prerequisite for carrying out the production process and the deformation is assumed as an output value in the mathematical model for description [10]. A sandwich-type structure is often used (for example, from LPCVD - $Si_3N_4$ and TEOS - $SiO_2$ - layers), in which tensile and compressive stresses are combined with an appropriate choice of layer thickness. The silicon oxynitride layers used in the PECVD process can be produced by optimizing the process parameters (gas pressure, gas mixing, power). Table 2. shows the process parameters for coating 1μm $Si_3N_4$.

TABLE 2 PROCESS PARAMETERS FOR COATING A SILICON SUBSTRATE

| Power, W | 100 to 13,56 MHz |
|---|---|
| Gas pressure, mTor | $650 \div 800$ |
| Substrate temperature, ˚C | 300 |
| Gas temperature, ˚C | 250 |
| Gas mixture | $80SiH_4$ / $80NH_3$ / $1000N_2$ |

The type of membrane material and thickness depend on complex factors. Very thin membranes (0.1 – 1 μm) with low thermal conductivity (~1W/mK) are obtained by PECVD and LPCVD methods from amorphous SiC, $Si_3N_4$, $SiO_2$ layers, if the aim is to achieve thermal insulation of the functional layers. Silicon membranes with a thickness of ~10 μm can be obtained by epitaxy and embedded stop-etch layers – basic structures for piezoresistive pressure sensors [10].
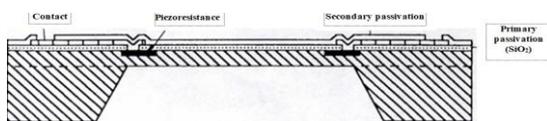


Fig. 2. Piezoresistive silicon pressure sensor.

TABLE 3 PROCESS SEQUENCE FOR MEMBRANE FABRICATION

| | |
|---|---|
| | Substrate |
| | Establishment of etch-stop layer by boron doping |
| | Establishment of epitaxial p-Si layer |
| | Oxidation |
| | Photolithography and trench opening |
| | Double-sided anisotropic etching |

## III. RESULTS AND DISCUSSION

Preferable options for graphic images and photographs are: 300 dpi resolution, 8 bits per pixel, grayscale.

A piezoresistive pressure sensor with a silicon membrane made by anisotropic etching on the reverse side of a silicon substrate is designed. The dimensions of the membrane are radius r = 2 mm; thickness b = 0.004 mm; pressure p = 0.1 N/mm$^2$.

The physicomechanical characteristics of the silicon (Si) material are: modulus of elasticity E = 1.9 . 10$^{11}$Pa, μ = 2,4.

The deformation of the membrane is considered in the linear region – $\delta_{max}$= ½ b, i.e. the boundary conditions of the load are determined.

When designing the structural parameters according to FEM, the membrane is considered as a firmly fixed thin elastic plate loaded with a distributed load p = 0.1 N/mm$^2$.

The mathematical description of a membrane is given by the membrane differential equation. It is derived by the Prantl analogy. The method of analogies is widely used in structural mechanics and in the theory of elasticity. The torsion function φ(x,y) is defined by the Poinson differential equation:

$$\frac{\delta^2 \varphi}{\delta X^2} + \frac{\delta^2 \varphi}{\delta Y^2} = -2Gv \qquad (1)$$

Where: δ is the angle of twist, rad; 2G – the multiple of the angle of twist, taken with a negative sign, rad.

Equation (1) is valid subject to the following boundary condition for displacement:

$$\varphi(s) = 0 \qquad (2)$$

From the equilibrium problem of an ideal membrane it is known that the vertical displacement ω(x,y) of an arbitrary point of it is determined by integrating the differential equation:

$$\frac{\delta^2 \omega}{\delta X^2} + \frac{\delta^2 \omega}{\delta Y^2} = -\frac{q}{H} \qquad (3)$$

Where: q is the distributed load acting on the membrane, N/mm$^2$; at the boundary condition:

$$\omega(s) = 0 \qquad (4)$$

The comparison of the differential equations and boundary conditions of the two problems shows that if we load the membrane with a distributed load q = 2HGõ, the function ω(x, y) will coincide with φ (x,y). In this way, the abstractly introduced function φ(x,y) becomes concrete and illustrative [16, 17].

The differential equation of the membrane (3) describes the mathematical model of the membrane deformation. FEM is used to solve a specific differential equation. According to it, the membrane is assumed to be an elastic plate, in which the bending stresses caused by the transverse forces are negligibly small compared to the tensile stresses lying in the midplane, which are large. In this method, the membrane is considered as a type of plate, i.e. it belongs to plates with a small thickness [20].

The differential equation of a thin elastic plate, which is from the second group of plate elements derived by FEM, is not of interest to us, because the membrane belongs to the third group of plate elements. It is derived by considering a thin elastic plate loaded with a distributed load q = q (x, y), acting along the z axis. The displacement function is ω = ω(x, y), which describes the deformation of the plate. After certain derivations and transformations, the desired differential equation is obtained:

$$\frac{\delta^4 \omega}{\delta X^4} + 2\frac{\delta^4 \omega}{\delta X^2 \delta Y^2} + \frac{\delta^4 \omega}{\delta Y^4} = \frac{q(X,Y)}{F} \quad (5)$$

The boundary conditions of the load must be determined. For this purpose, the possible stresses that satisfy the linearity condition will be determined. It is assumed that the membrane is firmly fixed.

It is known from the theory that in order to increase the accuracy of the solution obtained by FEM, it is necessary to apply a dense finite element mesh in the loaded area of the model under study. Since this area is not always known in advance, in practice, second and subsequent analyses are carried out in order to denser the mesh in the loaded areas and the results obtained for each subsequent analysis, after correcting the mesh, do not differ significantly within the required accuracy [18, 19].

The determination of the equivalent stresses of brittle materials, such as silicon (Si), is done using Moore's strength theory in a three-dimensional stressed state.

Moore's strength theory differs fundamentally from classical theories. It is based on the logical systematization of the results of the necessary experiments, and not on hypotheses regarding criteria for the occurrence of a dangerous state [6, 7].
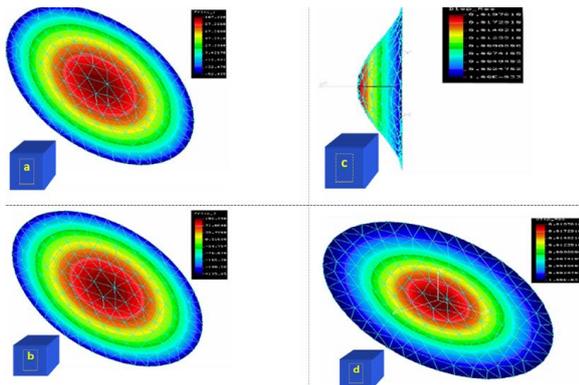


Fig. 3.

a) Principal normal stress $\sigma_1$, MPa; b) Principal normal stress $\sigma_3$, MPa; c) Distribution of total displacements, mm; d) Distribution of total displacements along the z axis, mm.

$$\sigma_{equivalent}^{IV} = \sigma_1 - k\sigma_3, MPa \quad (6)$$

$$\sigma_1 > \sigma_2 > \sigma_3 \quad (7)$$

The equivalent stresses are determined using formula (6).

From figure 3a, the axial stress is determined $\sigma_1=107,220$ MPa, and from figure 3b, the corresponding tangential stress $\sigma_3=106,340$ MPa.

The coefficient k is equal to 0.15.

$$\sigma_{equivalent}^{IV} = \sigma_1 - k\sigma_3 = 107,220 -$$

$$0,15 \cdot 106,340 = 91,27, MPa \quad (8)$$

$$\sigma_{equivalent}^{IV} = 91,27\, MPa < \sigma_{allowable} = 120MPa$$

From the results obtained, it follows that the equivalent stress is less than the allowable for the material. From theory it is known that tensile or compressive stresses (in this case tensile) are less than 5% of the bending stresses.

Figure 2 shows a piezoresistive pressure sensor with a silicon membrane fabricated by anisotropic etching of the reverse side of the silicon substrate. The strongest piezoresistive effect is observed at the location of maximum membrane deformation. Stoppers prepared by diffusion or ion implantation are used to form the active structure of the sensor. The silicon p-layer doped with a high boron content (concentration of boron impurities $5.10^{19}$ cm$^{-3}$) is etched much more. This possibility has been applied in the manufacture of the membrane, and by using etching processes at the protruding edges, bridge structures can also be obtained. Membranes with a small distance from the substrate surface can be made using surface layer mechanics methods. The most common material used is polysilicon with a structuring, subsequently removed by selective etching, sublayer of $SiO_2$ or PSG, which requires holes for access of the solution. This means that membranes without holes (profile cutouts) cannot be manufactured using this method. In addition to the polysilicon-based method, many variants with other materials for the layer have already been developed, for example $SiO_2$ layers under SOI substrates [8, 9].

Finally, let us present the following example of a typical technological process for the manufacture of a micromechanical element (MME)

Fig. 4 shows a MME flat membrane and a TP for its manufacture. Based on this TP, an example of a TTP for the manufacture of a group of flat round membranes with one-sided stoppers according to the MME classifier has been developed. The membrane in Fig. 4 is an element of a microcomponent (MC) piezoresistive pressure sensor.
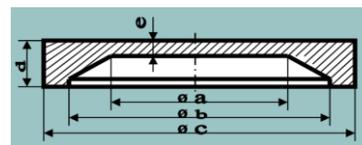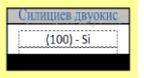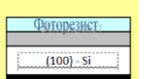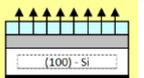


Fig. 4. Flat round membrane with one-sided stoppers

TABLE 4 TYPICAL TECHNOLOGICAL PROCESS FOR MANUFACTURING FLAT ROUND MEMBRANES WITH ONE-SIDED STOPPERS

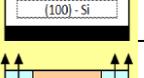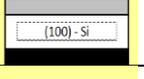| No. | Operation scheme | Operation code | Name of the operation |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1 | (100) - Si | | Preparing the substrate |
| 2 | p+ (100) - Si | 2.1.2.1 2.1.2.1.1 2.1.2.2.1 | Doping: Establishment of an etch-stop layer by doping with boron 1. By general diffusion 2. By ion implantation |
| 3 | Силициев двуокис (100) - Si | 2.1.1 2.1.1.1 2.1.1.2 | Oxidation: 1.Thermal oxidation 2. Anodic oxidation |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| 4 |  | 2.2.1<br>2.2.1.0.0.1 | Photolithography:<br>Surface preparation – washing and drying |
| 4 |  | 2.2.1<br>2.2.1.0.0.2 | Photolithography:<br>Deposition of photoresist |
| 4 |  | 2.2.1<br>2.2.1.0.0.3 | Photolithography:<br>Drying – removing the solvent and bringing the photoresist into a solid insoluble phase |
| 4 |  | 2.2.1<br>2.2.1.0.0.4 | Photolithography:<br>Combining the photopattern and exposing the positive resist under the influence of light passing into an insoluble phase |
| 4 |  | 2.2.1<br>2.2.1.0.0.5 | Photolithography:<br>Developing the photoresist – washing in solvent to remove the exposed resist |
| 4 |  | 2.2.1<br>2.2.1.0.0.6 | Photolithography:<br>Fixing – hardening of the resist and removal of solvent residues |
| 4 |  | 2.2.1<br><br>2.2.1.0.0.7 | Photolithography:<br>Local Etching – Through a Photoresist Mask<br>1. Liquid Local Etching<br>2. Dry Local Etching |
| 8 |  | 2.2.1<br><br>2.2.1.0.0.8 | Photolithography:<br>Photoresist Removal – "Stripping"<br>1. In boiling $H_2SO_4$<br>2. Gas and ionic |
| 5 |  | 2.3<br>2.3.1<br><br>2.3.2 | Local anisotropic etching<br>1. Liquid chemical anisotropic etching<br>2. Dry anisotropic etching |
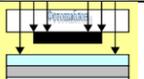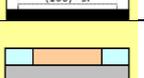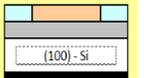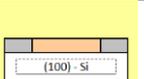
## IV. CONCLUSIONS

- A methodology for variant and generative design has been developed.
- A typical technological process for the production of flat round membranes with double-sided stoppers by double-sided anisotropic etching is presented and illustrated.
- A typical technological process for the production of flat round membranes with single-sided stoppers by double-sided anisotropic etching is presented.
- The recording of the generated information and a typical technological process in the database of an automated system for the design of microsystems equipment products "MICROSYS 25" is presented.

### ACKNOWLEDGMENTS

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