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Functional model for the synthesis of nanostructures of the given quality level

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ABSTRACT

Purpose: The aim of this paper is to develop a functional model for the synthesis of nanostructures of the given quality level, which will allow to effectively control the process of nanopatterning on the surface of semiconductors with tunable properties.

Design/methodology/approach: The paper uses the IDEF0 methodology, which focuses on the functional design of the system under study and describes all the necessary processes with an accuracy sufficient for an unambiguous modelling of the system's activity. Based on this methodology, we have developed a functional model for the synthesis of nanostructures of the given quality level and tested its effectiveness through practice.

Findings: The paper introduces a functional model for the synthesis of nanostructures on the surface of the given quality level semiconductors and identifies the main factors affecting the quality of nanostructures as well as the mechanisms for controlling the formation of porous layers with tunable properties. Using the example of etching single-crystal indium phosphide electrochemically in a hydrochloric acid solution, we demonstrate that the application of the suggested model provides a means of forming nanostructures with tunable properties, assessing the quality level of the nanostructures obtained and bringing the parameters in line with the reference indicators at a qualitatively new level.

Research limitations/implications: Functional modelling using the IDEF0 methodology is widely used when process control is required. In this study it has been applied to control the synthesis of nanostructures of the given quality level on the surface of semiconductors. However, these studies require continuation, namely, the establishment of correlations between the technological and resource factors of synthesis and the acquired properties of nanostructures.

Practical implications: This study has a significant practical effect. Firstly, it shows that functional modelling can reduce the time required to form large batches of the given quality level nanostructures. This has made it possible to substantiate the choice of the initial semiconductor parameters and nanostructure synthesis modes in industrial production from the theoretical and empirical perspective. Secondly, the presented methodology can be applied to control the synthesis of other nanostructures with desired properties and to reduce the expenses required when resources are depleted and the cost of raw materials is high.

Originality/value: This paper is the first to apply the IDEF0 methodology to control the given quality nanostructure synthesis. This paper will be of value to engineers who are engaged in the synthesis of nanostructures, to researchers and scientists as well as to students studying nanotechnology.

Keywords: Functional model, Electrochemical etching, Quality level, Semiconductors, Nanostructures, IDEF0 methodology

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Nanotechnology is steadily advancing from laboratory research to industrial use [1,2]. Today, lasers [3,4], solar cells [5,6], electronic devices [7,8], etc. are being developed based on nanostructures. Porous semiconductors [9,10], nanowires [11,12], whiskers [13,14], thin films [15,16], superlattices [17,18], quantum dots [19,20] have already found their industrial application. The most frequently used materials for the synthesis of nanostructures are Si [21,22], CdTe [23,24], GaAs [25,26], SiC [27,28], InP [29,30], ZnO [31,32], etc.

However, there is a number of challenges when using nanostructures in actual manufacture associated with the imperfection of technologies for the synthesis of nanostructures [33,34], the presence of defects on the surface and in the nanomaterial itself [35,36], nonstoichiometric composition [37,38] and instability of surface layers [39,40]. With this in mind, it is necessary to develop technologies for managing the quality of nanostructures. Control should be exercised from designing experiments to launching industrial batches, that is, at each stage of the nanomaterial synthesis.

In this aspect, the quality of nanotechnology products should be understood as the degree of the product characteristics that meets the specified requirements [41]. Therefore, it is advisable to define a given quality level as the correspondence of the assessed quality indicators to the established (reference) values. Quality assurance is an integral part of the overall product quality management system [42]. That is, the given product quality level is a consequence of the entire quality management system.

Therefore, in order to obtain high-quality nanostructures with the given tunable properties, it is necessary to create a system for ensuring the quality of nanostructures through managing the nanostructure synthesis process itself. We will consider the synthesis of nanostructures as a process implemented in a certain time interval and in a certain sequence in accordance with the specified stages.

Quality criteria are determined by decomposing the system of quality criteria for each structural level, taking into account its purpose [43].Controlling technological factors are established based on the analysis of the results of decomposing the properties at each structural level [44].The dependences of the influence of controlling technological factors on the properties of a material are reflected in the experimental-statistical models, the totality of which is a general model for ensuring the quality of the synthesized nanostructures [45].

The quality of nanomaterials, namely the quality of preparing the nanostructured surfaces for further use by the consumer, is closely related to the quality of technological processes. These processes include [46,47]:

- evaluating the quality of the virgin wafer;
- synthesizing nanostructures of a given quality level;
- current assessment of the nanostructure synthesis;
- final assessment of the quality of nanostructures reflected in incoming control;
- correcting the procedures and improving quality indicators of the formed nanostructures.

The necessary and sufficient set of quality indicators for nanostructures and the addition of new properties should consist of such quality indicators that affect the effectiveness, that is, the achievement of the desired result [48]. In this sense, interconnected processes should be represented as the system components. Each of the components of the quality management system for nanostructures is a complex subsystem characterized by its tasks, functions and means of implementation. That is, the following is required [49,50]:

- description of the structure of the implementation processes;
- definition of the system functions;
- establishment of the system properties.

In the given study, introduces a functional model for the synthesis of nanostructures on the surface of the given quality level semiconductors and identifies the main factors affecting the quality of nanostructures as well as the mechanisms for controlling the formation of porous layers with tunable properties.

2. Work methodology

Being the topology of describing the system as a whole as a set of interrelated actions or functions [51], the IDEF0 (ICAM Definition) methodology can be applied as a methodological foundation. The IDEF0 graphics standard is part of the SADT (structural analysis and design technique) methodology [52]. The main goal of this methodology is to construct a functional diagram of the system under study describing all the necessary processes with an accuracy sufficient for unambiguous modelling of the system's activity. In the IDEF0, a model is a description of a process network.

At the first stage of building a functional model using the IDEF0, it is necessary to define a function that is a process. The definition of this process is carried out through the goal formation. The goal, in turn, reflects the reason for building the process model and determines its purpose. The overall goal of the models within the IDEF0 methodology is to analyse the compliance of the resulting model with the established requirements. In order to identify the processes, it is necessary to determine the parameters of the nanostructure; the functional purpose of nanoproducts; the objects of transformation (semiconductor wafers).

Based on this information, we can identify the main function (process), "Synthesizing Nanostructures of the Given Quality Level" (Fig. 1).

Functional modelling involves a gradual transition from general to specific by decomposition. The context diagram contains a description of the activity (synthesizing nanostructures of the given quality level) permeated by flows connecting the subject of this activity (nanostructures) and the process, that is, the model itself, with the real environment.

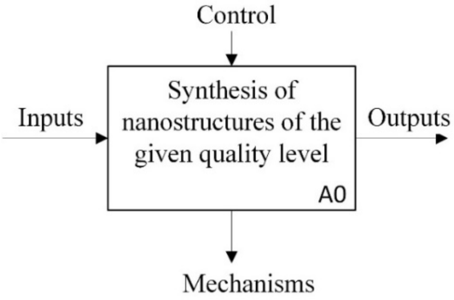

Fig. 1. Setting the function of the nanostructure synthesis

The inputs for the synthesis of nanostructures on a semiconductor surface of a given quality level are: semiconductor wafers; consumers of products (devices in which nanostructures will be used); resources; external information about the state of the original semiconductor samples.

The outputs of the process are: synthesized nanostructures of the given quality level; consumers (devices in which synthesized quality nanostructures can be used); profit and payback from applied technological innovations; information for consumers (assessment of the quality level of nanostructure parameters and compliance with the functional purpose).

The process is controlled based on the standards, technological routes, quality criteria and the like. Mechanisms include external influences, personnel and available equipment for the synthesis of nanostructures. The process map is shown in Figure 2.

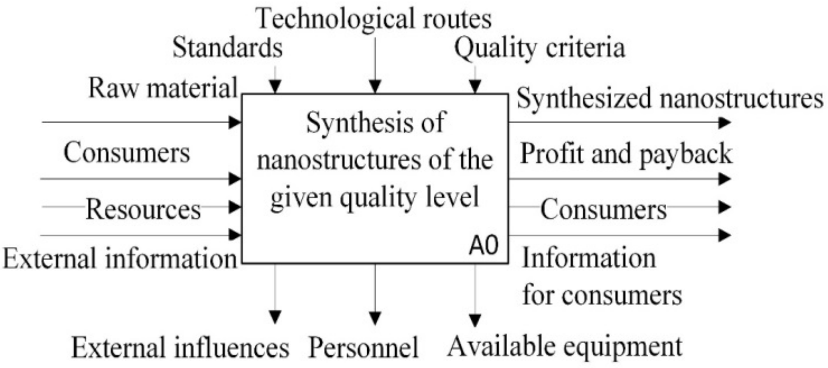

Fig. 2. Context diagram of the Synthesis of nanostructures of the given quality level

Taking into account the goals of modelling (compliance of the process with the regulatory requirements), the “Synthesizing Nanostructures of the Given Quality Level” process includes the following functions (processes): quality management; resource management; synthesis control; evaluating and improving quality.

Let us consider the interactions between the processes that make up the “Synthesizing Nanostructures of the Given Quality Level” process (Fig. 3).

The “Quality Management” A1 function is the control function for all other functions. Accordingly, the “Requirements, Instructions” outputs are the control function for all other functions of the system. The “Resource Management” A2 function has an “output-mechanism” interaction with the “Synthesis Control” A3 function. In turn, the output of the “Synthesis Control” A3 process is the input to the “Evaluation and Quality Improvement” A4 function.

The outputs of the “Evaluation and Quality Improvement” A4 function will be: nanostructures of a given quality level; consumers (devices); information on the quality of nanostructures and payback of technological operations for the synthesis of nanostructures.

Further, there is decomposition for all four functions: “Quality Management” A1, “Resource Management” A2, “Synthesis Control” A3, “Evaluation and Quality Improvement” A4.

The quality of nanostructures will be determined by the technological factors of synthesis; therefore, we will consider the structure of the process network making up the “Synthesis Control” A3 function (Fig. 4).

The input of the “Incoming Quality Assessment” A.3.1 process receives information about the materials that are used for the production of nanostructures, that is, semiconductor wafers. Information about the wafer parameters is obtained from the material safety data sheet, or by testing non-destructively the properties of the semiconductor that will affect the initial properties of the synthesized nanostructures.

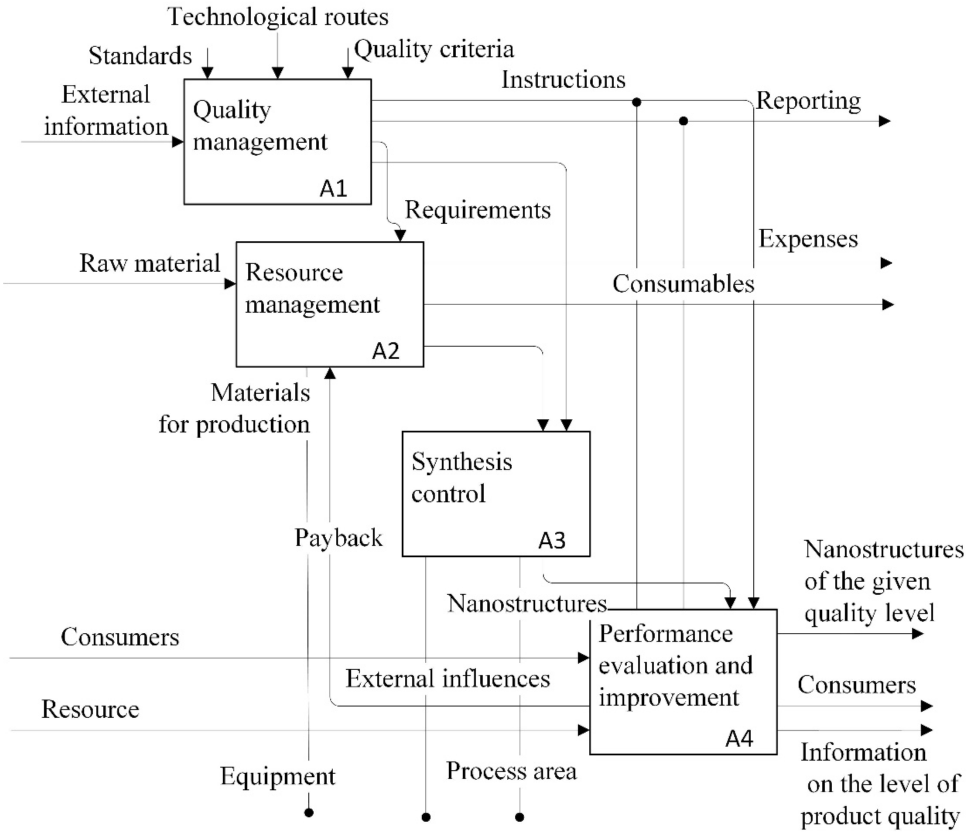

Fig. 3. Decomposition of the “Synthesizing Nanostructures of the Given Quality Level” process

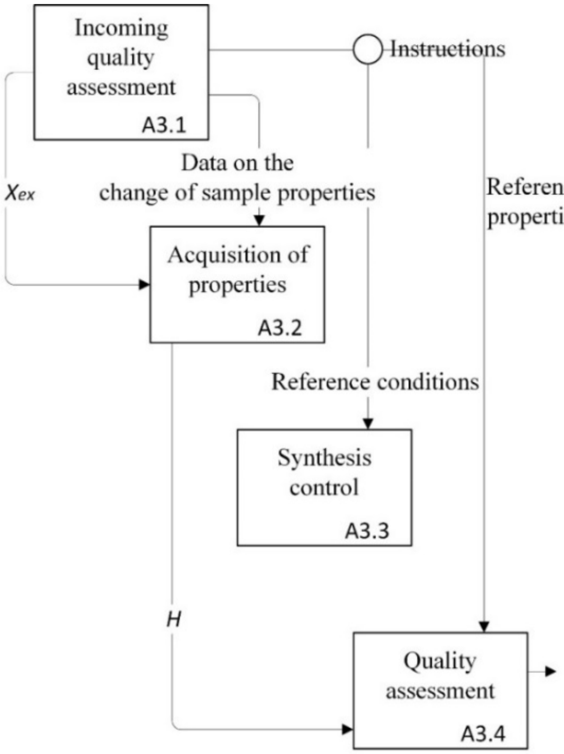

Fig. 4. The structure of the process network making up the “Synthesis Control” function

3. Description of achieved results of own researches

The set of properties of the original sample is the variety of partial properties and can be represented by the set of indicators:

$$\chi = \sum_{i=1}^{n} f(\alpha_i), \tag{1}$$

where n – the number of properties being evaluated, α_i – properties of the sample, each of which, in turn, can be represented by the set of indicators:

$$\begin{cases} \alpha_1 = \alpha_{11} + \alpha_{12} + \ldots + \alpha_{1k} \\ \alpha_2 = \alpha_{21} + \alpha_{22} + \ldots + \alpha_{2l} \\ \alpha_m = \alpha_{m1} + \alpha_{m2} + \ldots + \alpha_{mp} \end{cases}, \tag{2}$$

where $k, l, m, p \in N$.

These include: type of semiconductor conductivity, surface orientation, doping level, type of dopant, type and number of defects, etc.

Naturally, the original samples are characterized by a certain quality level; there may be defective samples in the batch or those that do not partially meet the specified parameters. Therefore, it is necessary to have the set of initial indicators of the sample properties, which will be considered as a reference. Proceeding from this, it is possible to determine the function of the “Incoming Quality Control” A3.1 process by comparing the properties included in the original set of sample properties with the properties included in the reference set of sample properties through checking if falls within the interval of reference values:

$$\chi \in \left[\chi_{st\min}; \chi_{st\max}\right], \tag{3}$$

where $\chi_{st\min}$ – minimum allowable reference value of the property,

$\chi_{st\max}$ – maximum allowable reference value of the property.

When synthesizing nanostructures on the surface of semiconductors, some properties change significantly, and others completely lose their meaning (for example, surface smoothness). In addition, a semiconductor wafer with a layer of nanomaterial on the surface acquires completely different properties compared to those of the output crystal. Therefore, in a certain approximation, one more characteristic can be introduced, $\Delta\chi$ – the increment of the property function of the original set of sample properties. This value is described by the variety of its indicators.

$$\Delta\chi = \left\{\Delta\chi_1, \Delta\chi_2, \ldots \Delta\chi_m\right\}, \tag{4}$$

where

$$\begin{cases} \Delta\chi_1 = \Delta\chi_{11} + \Delta\chi_{12} + \ldots + \Delta\chi_{1k} \\ \Delta\chi_2 = \Delta\chi_{21} + \Delta\chi_{22} + \ldots + \Delta\chi_{2l} \\ \Delta\chi_m = \Delta\chi_{m1} + \Delta\chi_{m2} + \ldots + \Delta\chi_{mp} \end{cases}, \tag{5}$$

where $k, l, m, p \in N$.

That is, the increment of the property function of the original set of $\Delta\chi$ sample properties is the output of the “Incoming Quality Assessment” A3.1 process. The information contained in the form of the increment of the property function of the original set of $\Delta\chi$ sample properties is the controlling factor for the “Acquisition of Properties” A3.2 process.

The original set of conditions for the formation of T nanostructures is a set of conditions provided by the stages of the technological process.

As mentioned earlier, the original properties of the sample not only change, but also acquire new properties. According to the basic principles of the IDEF0 notation, the input of the "Acquisition of Properties" process receives many original parameters of χ sample, that is, those parameters of the semiconductor that it possessed before its technological processing.

Based on these documents, a set of technological factors is formed:

$$\mathrm{T} = \sum_{i=1}^{n} f\left(\tau_i\right), \tag{6}$$

where k – the number of conditions for the formation of nanostructures.

The function of the "Acquisition of Properties" process is described as follows:

$$H = \left\{h_1, h_2, ..., h_m\right\}, \tag{7}$$

which is described by a set of attributes:

$$\begin{cases} h_1 = h_{11} + h_{12} + \ldots + h_{1k} \\ h_2 = h_{21} + h_{22} + \ldots + h_{2l} \\ h_m = h_{m1} + h_{m2} + \ldots + h_{mp} \end{cases}, \tag{8}$$

where $k, l, m, p \in N$.

The outputs of the "Acquisition of Properties" A3.2 process are: the set of initial properties of the sample, the set of acquired properties of the sample.

Of course, certain technological operations are carried out during the technological process of nanostructure synthesis. These operations must be controlled throughout the entire technological process. Therefore, taking into account the current assessment is an important link in ensuring the quality of the synthesized nanostructures.

The function of the A3.3 process, which arises in determining whether the model of the technological process of nanostructure synthesis falls within the range of values of the reference model, can be represented as follows:

$$\mu \in \left[\mu_{st\,\min}; \mu_{st\,\max}\right], \tag{9}$$

where μ – technological process model;

$\mu_{st\,\min}$ – minimum allowable reference value of the reference technological process model,

$\mu_{st\,\max}$ – maximum allowable reference value of the reference technological process model.

The outputs of the "Synthesis Control" A3.3 process will be the estimates of the technological process model, that is, information about the quality of the "Synthesis Control" A3 process.

The "Quality Assessment" A3.4 process is the final one for the A3 process. At this stage, it is necessary to understand the technological process flow, evaluate its features and draw a conclusion about the possibility to repeat the experiment and reproduce the results. This process precedes the final stage, that is, the overall assessment of the activity, and is an important link in the overall process of managing the quality of nanostructures. The input of the "Quality Assessment" A3.4 process receives a set of acquired properties of sample H. The function of this process is to compare the acquired properties of nanostructures with reference ones. Achievement of the result will be characterized by falling into the interval of reference values of the acquired properties of the sample:

$$H \in \left[H_{st\,\min}; H_{st\,\max}\right], \tag{10}$$

where $H_{st\,\min}$ – minimum allowable reference value of the acquired properties,

$H_{st\,\max}$ – maximum allowable reference value of the acquired properties.

The outputs of the "Quality Assessment" A3.4 process will be the estimates of the initial set of acquired properties of the sample, that is, information about the quality of the "Synthesizing Nanostructures" A3 process. The consumer information will be assessing the initial set of acquired properties of nanostructures.

The core of the "Synthesizing Nanostructures" A3 process is the "Implementing Property Additions" A3.2 process. The generalized quality indicator will contain partial criteria consisting of partial indicators. That is, the partial criterion performs the function of comparing the acquired properties of the sample with the reference values.

Accordingly, the criterion for the synthesis process completion can be the reference range of values.

The performed functional modelling and installation of the functions presented in formulas (1)-(10) have an important technological purpose. First, the decomposition of the system allows to estimate with high accuracy all the factors affecting the quality level of the synthesized nanostructures. Second, for the serial production of nanostructures it is necessary to unify the requirements for technological processes, crystal parameters, expected indicators. Third, it is promising to create a computer model based on functions (1)-(10), which will make it possible to predict the results of activities in advance and synthesize nanostructures of a given quality level on various semiconductors. The applicability of this model will be tested on the example of the synthesis of mesoporous indium phosphide.

4. Experimental results and discussion

For the experiment, we have used 4 batches of samples of single-crystal indium phosphide grown by the Czochralski method, each batch containing 20 samples (Tab. 1).

Table 1.
Batches of samples used in the experiment

No	Parameters	1 batch	2 batch	3 batch	4 batch
1.	Conduction type	n-type	n-type	n-type	n-type
2.	Impurity concentration (S), cm^{-3}	$2.3x10^{18}$	$2.3x10^{18}$	$1.2x10^{19}$	$1.2x10^{19}$
3.	Surface orientation	(111)	(100)	(111)	(100)

Incoming quality control of the samples consisted of the following stages:

(1) Visual inspection: the presence of chips, cracks, scratches, irregularities. At this stage, each sample (80 samples) has been examined.

(2) Selective electrochemical etching in hydrofluoric acid solution. At this stage, 10 samples have been randomly selected from each batch. The samples have been evaluated using a scanning electron microscope. Table 2 shows the number of yields of defective samples.

Table 2.
The number of yields of defective samples during the 1st and 2nd stages of incoming control

1 batch	2 batch	3 batch	4 batch
The number of defective samples at the 1st stage of incoming control			
1 (5%)	0 (0%)	3 (15%)	2 (10%)
The number of defective samples at the 2nd stage of incoming control			
4 (40%)	0 (0%)	6 (60%)	4 (40%)

At the first stage of control, the presence of defective samples (which had chips) was established, with the largest number of them in batches 3 and 4 (samples 3 and 2, respectively). Figure 5 shows an example of a sample with a chip. A sample is considered to be defective if at least one surface defect is observed during visual inspection. The fact is that mechanical defects are the centres of the appearance of additional stresses, have broken chemical bonds, and so on. This leads to uneven etching of the crystal and can significantly affect the formation of a porous layer on the surface of indium phosphide.

Fig. 5. Example of a defective sample from batch 3 (orientation (111), impurity concentration $1.2x10^{19}$ cm^{-3}): on the surface you can see a chip formed as a result of improper use of the sample and due to the fragility of the plate

We can make a conclusion that high doping levels result in the decrease in the wafer durability and it becomes more brittle. Also, durability depends on the crystallographic orientation of the surface.

Samples with orientation (100) are more durable than (111)-oriented samples. This is due to the fact that (111)-oriented samples have excess stresses on the surface, the sources of which are areas of compositional inhomogeneity. On the other hand, samples with high doping levels show the ability to segregation. This is the result of microfluctuations of growth rates at the boundary between the solid and liquid phases during crystal growth by the Czochralski method [53].

The results of the second stage of incoming control during selective electrochemical etching indicate that etching pits emerge along the radial lines on the surface of the samples with the surface orientation (111). The higher the doping level of the crystal, the more etching pits. This demonstrates the uneven distribution of the dopant and the presence of segregation lines. We can make a conclusion that it is advisable to use samples of batch No. 2 in order to form an even porous layer on the surface of indium phosphide.

Thus, incoming control has allowed us to reject 3 batches of samples due to inconsistencies in the input parameters. After incoming control, the samples of batch No. 2 contain two groups: 5 samples that have undergone selective etching and 15 samples that have not been treated.

In order to implement the next stage, “Acquisition of Properties”, it is necessary to determine which properties will act as reference and what technological factors will ensure the acquisition of such properties.

The estimated properties of the synthesized nanostructures include porosity, pore size and shape (shape factor). Reference values are determined taking into account the functional purpose of the material. For industrial use of nanostructures, it is appropriate to choose samples with an average porosity level and mesopores with a circular cross-section (Tab. 3).

The analysis of literature sources [54-56] indicates that it is advisable to use simple electrochemical etching in a hydrochloric acid solution for the formation of nanostructures with the indices specified in Table 3. The reference synthesis conditions are defined in Table. 4.

Table 3.
Reference values of quality indicators of indium phosphide nanostructures

No	Indicator	Value
1.	P, porosity	(50-70)%
2.	d, pore size	(20-50) nm
3.	F, shape factor	1

Table 4.
Reference synthesis conditions

No	Technological factor	Value, indicator
1.	Electrolyte	H_2O+HCl
2.	Acid concentration in solution	5%
3.	Etching time	10 min
4.	Light	No light, etching in a darkroom
5.	Solution temperature	20°C
6.	Air temperature	20°C
7.	Current density	150 mA/cm^2

All samples not rejected after the first stage have been subjected to electrochemical treatment: 10 “pure samples” (P) from each batch and samples after selective electrochemical etching (SE) 5, 10. 1, 4 samples from batches 1-4, respectively. Electrochemically treated samples falling within the morphological reference values are shown in Table 5.

The results of Table 5 allow conducting a detailed analysis of the synthesis of nanostructures as well as assessing the quality of the samples obtained. Let us focus only on the most essential results. Electrochemical etching of samples with surface orientation (111) has had no desired effect; only 1 sample from two batches (batch 1 and batch 3) meets the established reference values. Macropores of elliptical or triangular shape with high density have been formed on the surface of such samples (Fig. 6). In this case, the process of pore growth in depth is slowed down by the fact that the [111] direction, which is perpendicular to the surface, has the lowest reaction rate. Therefore, the pores are located at an angle to the surface and tend to merge and form agglomerates [57]. After etching, samples with surface orientation (100) have had round pores on the surface (Fig. 7). In this case, the etching front is directed deep into the substrate. The direction [100] corresponds to the maximum etching rate. The pores move deep through thin inter-parallel channels [58,59]. The impurity concentration is also a decisive factor in the compliance of samples with the reference value; samples with a higher impurity concentration demonstrate a much lower yield of effective samples. For batch 2, preliminary selective etching has not had a decisive role in the yield of effective samples. For batch 4, selective etching has had a negative impact on the quality of the samples.

Table 5.
The number of samples and their percentage corresponding to the reference values

No	Indicator	Batch 1		Batch 2		Batch 3		Batch 4	
		1 P	1SE	2 P	2 SE	3 P	3 SE	4 P	4 SE
1.	Number of samples	10	5	10	10	10	1	10	4
2.	Porosity	5 (50%)	3 (60%)	10 (100%)	9 (90%)	3 (30%)	1 (100%)	9 (90%)	2 (50%)
3.	Pore size	1 (10%)	0 (0%)	9 (90%)	9 (90%)	0 (0%)	0 (0%)	6 (60%)	1 (25%)
4	Shape factor	2 (20%)	0 (0%)	10 (100%)	10 (100%)	2 (20%)	0 (0%)	10 (100%)	4 (100%)
5	Number and percentage of effective samples upon all three indicators	1 (1%)	0 (0%)	9 (90%)	9 (90%)	0 (0%)	0 (0%)	6 (60%)	1 (25%)

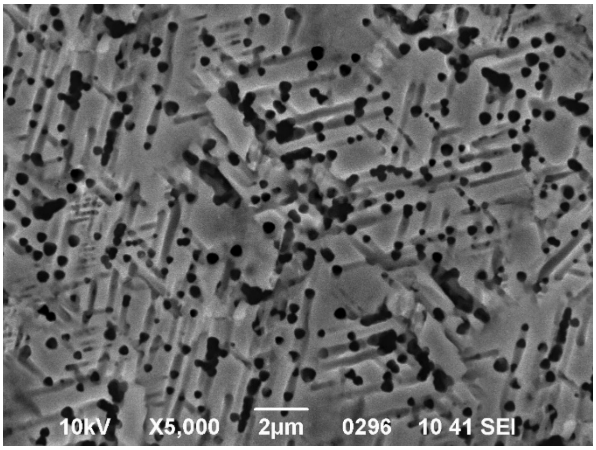

Fig. 6. SEM image of the porous InP (111) surface with an impurity concentration of 2.3x10^{18} cm^{-3}

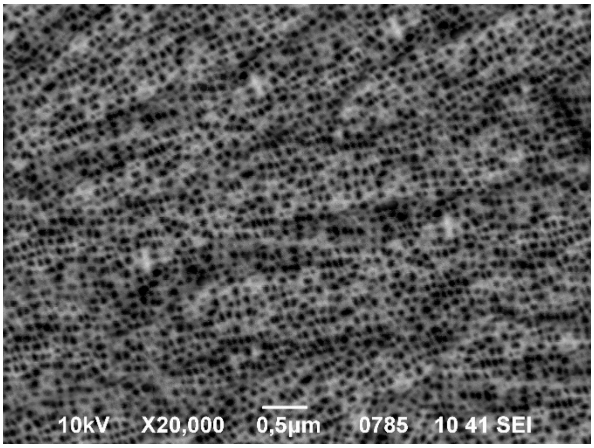

Fig. 7. SEM-image of the porous InP (100) surface with an impurity concentration of 2.3x10^{18} cm^{-3}

The results obtained have substantiated the expedience to reject samples of batches No. 1, No. 3 and No. 4 immediately following the stage of incoming control. Thus, incoming control helps reduce costs and time.

Based on the analysis conducted, a number of corrective actions can be identified for further activities. In order to form nanostructures on the surface of indium phosphide with the established reference values of morphological parameters (circular cross-section mesopores with an average porosity level), it is recommended to select samples with a surface orientation (111) and an impurity concentration of 2.3x10^{18} cm^{-3}. Optimal etching conditions: 5% hydrochloric acid solution, etching at a current density of 150 mA/cm^2 for 10 min at room temperature in a darkroom.

Thus, we have demonstrated an example of using the IDEF0 notation to control the synthesis of nanostructures on the surface of single-crystal indium phosphide with predetermined properties. At the same time, a number of important stages and restrictions have not been taken into account. A detailed analysis and consideration of all factors cannot be carried out within the framework of a single paper. Nevertheless, one can see that the suggested approach allows controlling the synthesis of nanostructures with given properties as well as identifying common synthesis patterns and factors affecting the quality of nanostructures.

5. Conclusions

1. Controlling the quality of nanostructures and establishing the reference values that ensure their operational suitability are vital for their industrial use. We suggest using the IDEF0 notation to control the synthesis of nanostructures on the surface of the given quality level semiconductors, which allows identifying the main stages of the technological process as well as factors affecting the quality of nanostructures.
2. Based on the "Synthesizing Nanostructures of the Given Quality Level" functional process diagram we have developed a process network that makes up the "Synthesis Control" function. Such diagram has allowed identifying the main factors that must be taken into account in the synthesis of nanostructures with controlled properties.
3. To experimentally verify the model developed for quality control of nanostructures, we have synthesized certain nanostructures, namely, porous layers on the surface of n-type indium phosphide. We have selected 4 sample batches with different initial parameters. As a result, it has been discovered that a porous layer is formed on the semiconductor surface when treating the wafers of single-crystal indium phosphide electrochemically in a hydrochloric acid solution.
4. We have determined the reference values of the quality indicators of the synthesized nanostructures and have tested the number of samples with parameters falling within the interval of such reference values.
5. It has been established that selective electrochemical etching is a reliable method for detecting defective samples. Samples with a high doping level and surface orientation (111) do not fall within the reference values. On the other hand, selective electrochemical etching does not affect the further quality of the synthesized nanostructures.
6. When treating the crystals electrochemically in a hydrochloric acid solution, it has been possible to form

porous layers consisting mainly of circular cross-section mesopores with an average porosity level. The highest quality structures have been formed on samples with a crystallographic orientation (100) and an impurity concentration of $2.3\text{x}10^{18}$ cm^{-3}.

7. The suggested technique for functional modelling of the quality control process for nanostructures can be applied to a wider range of nanomaterials.

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