Training Prospective Nanotechnologists to Select Optimum Solutions for the Nanostructures Synthesis Using the Analytic Hierarchy Process

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Abstract **– Nanotechnologists are in great demand and this need is becoming more and more acute every year since nanomaterials have gained widespread acceptance in various industries. The specificity of nanotechnology is determined by a wide variety of existing nanomaterials and technologies for their synthesis. The study suggests an efficient technique for training prospective nanoengineers to make managerial decisions in the synthesis of nanostructures. Moreover, the article demonstrates that using T. Saati's hierarchy analysis method offers the optimum solution for obtaining nanostructures. The analysis is based on the most commonly used synthesis technologies such as chemical etching, photoelectrochemical etching and imprint lithography.**

The application of T. Saati's method allows prospective nanoengineers to optimize the synthesis of high-quality nanostructures as well as ensure an economic and competitive advantage and reduce the number of errors.

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1. Introduction

The modern rapid development of technological industries creates a need for the higher-education system to train competent nanotechnologists capable of practically applying the latest advances in modern science [1], [2], creatively using and obtaining innovative nanomaterials [3], [4] as well as introducing nanotechnologies [5], [6]. However, the expert training system nowadays faces a contrariety between the demand for highly qualified nanotechnologists [7], [8] well positioned to create [9] and use [10] innovative nanomaterials and nanotechnologies and the insufficient level of their professional competence in the context of a traditional training system [11].

Today, nanotechnologists are trained within a cross-disciplinary framework. Modern-day experts must have a good grasp of the methods and theory of basic sciences, namely biology, chemistry, physics and mathematics [12], [13]. On the other hand, the nanotechnology industry requires its prospective experts to gain specific knowledge and skills including but not limited to the ability to work with large amounts of data [14], competently use the software [15], master the synthesis of nanostructures [16] and investigate their physical [17], electrical [18] and chemical [19] nature.

This need is primarily due to the variety of nanostructures and technologies for their synthesis, consequently. According to StatNano, there are 43 types of nanostructures successfully used in the creation of more than 9000 unique products [19].

Each of the types of nanostructures contains subcategories with their inherent and unique properties [20]. This perplexes the selection of methods most suitable for the synthesis of nanostructures and technological modes. For this reason, the nanotechnology industry remains the most science-intensive nowadays and requires the training of experts with unique competencies [21].

Higher efficiency of expert training can be achieved by directly involving applicants in scientific-research and production activities in the nanotechnology domain, namely the design of devices for the synthesis of nanostructures [22], the synthesis of nanostructures [23], the study of their properties [24] as well as the prediction of the actual application of the synthesized nanomaterials [25].

Educational institutions aim at ensuring that prospective nanotechnologists are capable of competently engaging in the innovative creation of new nanomaterials samples with tailor-made properties for their subsequent use in specific industries. It is necessary to use a systematic approach in developing the required competence given the extremely large-scale information scope to be absorbed by prospective nanotechnologists within a brief master training time.

Hierarchy analysis method is widely used by nanotechnologists for determining the regularities and selecting the optimum solution in the synthesis of new samples of high quality nanomaterials [26], [27]. This method is based on comparing the available alternatives in order to choose the optimum solution [28]. The given study suggests that applicants indulging in nanotechnology training programs use this method to optimize the processes of nanostructures synthesis.

Developing the ability to make optimum managerial decisions based on the hierarchy analysis method is substantiated by selecting among three typical methods for the synthesis of nanostructures on the surface of semiconductors, namely chemical etching (CE) [29], [30], photoelectrochemical etching (PEC) [31], [32] and imprint lithography (IL) [33], [34].

2. Research Methodology

Nanomaterials Representative Model

A systematic approach in the training of prospective nanotechnologists with regard to the synthesis of nanostructures allows one to structure, systematize and summarize multifarious educational information from a large number of existing nanomaterials, technologies and tailor-made tools as well as their numerous application niches.

Any functional material can be characterized by a set of parameters, namely composition (C_0), structure (S_0), properties (P_0) and functionality (F_0). It is crucial to control the synthesis conditions when forming nanostructures on the surface of the base material, i.e., their technological (R_0) and prescription (H_0) factors. The output parameters of the base material (P_0) as well as the synthesis conditions (T) serve as prerequisites for acquiring new properties during nanopatterning, that is, their acquired parameters $P_1\{C_1, S_1, P_1+P_1', F_1\}$. The Nanomaterials Representative Model is structured in its form (Figure 1.):

$$P_0\{C_0, S_0, P_0, F_0\}+T(R_0, H_0)=P_1\{C_1, S_1, P_1+P_1', F_1\}.$$

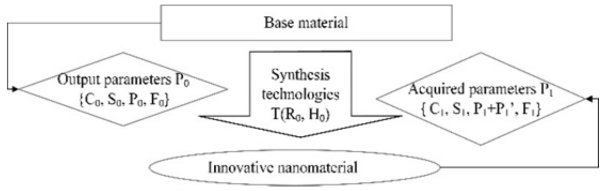

Figure 1. Nanomaterials Representative Model

With this approach, the algorithm for the innovative synthesis of any new nanomaterial provides for the analysis of already existing standard samples, similar to what needs to be created as to their purpose (practical application), composition (structure), functional principle and properties as well as their synthesis technologies. The further identification of patterns between the properties of existing samples of nanomaterials and their synthesis technology allows one to select the most optimum technology suitable according to a number of parameters, and subsequently adjust some of its conditions.

Hierarchy Analysis Method in Selecting the Optimum Technology for the Synthesis of Nanostructures

The hierarchy analysis method bases itself on decomposition of the problem into simpler constituent parts and the subsequent processing of judgments at each hierarchical level using pairwise comparisons [35]. As a result, one can observe either a relative degree (intensity) of interaction between elements in the analysed hierarchical level or the predominance of some elements over others. This approach allows prospective nanotechnologists to both evaluate the results of their practical activity and develop some useful predicting skills.

The first stage of hierarchical synthesis incents the students to analyse the available alternatives. The second stage presupposes the construction of the criteria hierarchy with the goal being finally set at the highest hierarchy level (i.e., the third stage). One should necessarily demonstrate to the students that the set goal is achieved through the intermediate hierarchy levels (criteria) to the lowest level (set) of available alternatives (Figure 2.).

Structural elements of any hierarchical level must be arranged in matrices of pairwise comparisons. Comparison results are indicated in numbers in each matrix cell determined by the Saati scale (Figure 3.).

Hierarchical levels are characterized by their inherent priority vector. For convenience, it is expedient to operate with standardized values of w_i (i=1,…,n) with the following properties:

$$w_1+w_2+\ldots+w_n=1. \quad (1)$$

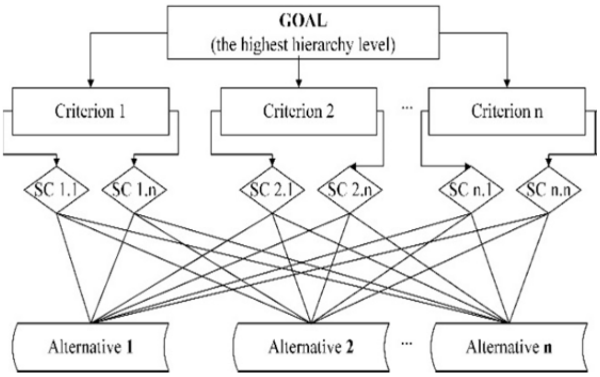

Figure 2. Hierarchical Model of the Hierarchy Analysis Method

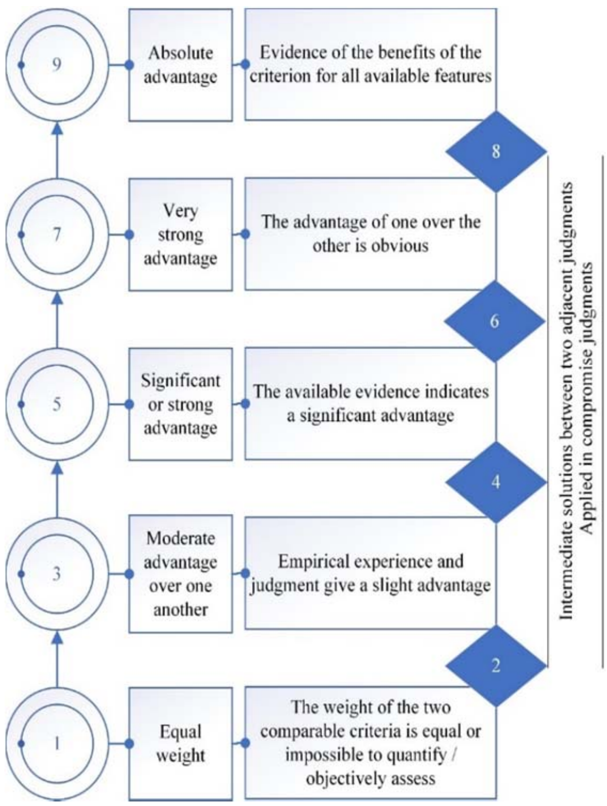

Figure 3. Relative Significance Scale

When using standardized values, one should take into account that wi ·100% indicates the criterion weight (factor) expressed as a percentage meaning that the matrix of pairwise comparisons is an assessment of the measure of significance of one criterion over another. As a result, we have a vector of generalized priorities pertaining to the analysed alternatives and thus defining the advantages for achieving the main goal.

3. Results

Selection of Evaluation Criteria

In order to successfully apply the hierarchy analysis method when selecting the optimum technology for the synthesis of nanostructures on the surface of semiconductors, one should necessarily focus on selecting the evaluation criteria (Table 1.) and providing a brief description.

Table 1. Criteria for determining the optimum technology for the synthesis of nanostructures by Hierarchy Analysis Method

No.	Criterion	Interpretation
1	Effectiveness C_{eff}	Demonstrates the extent to which the synthesized nanostructures correspond to the reference parameters, i.e., indicates the quality of the synthesis process
2	Simplicity C_{si}	Takes into account the number of technological stages and steps as well as the need for high-tech equipment and staff competence. The simpler the technology, the better
3	Time C_t	Indicates the time required for technological operation from the moment of sample preparation to obtaining the final result
4	Cost-effectiveness C_{cost}	Includes data on the used resources and related expenses, etc. Indicates the balance between the cost of technology and the obtained result

As demonstrated in Table 1., each criterion contains a number of sub-criteria with such sub-criteria not being calculated for the sake of simplicity but rather qualitatively taken into account when assessing their impact on each criterion. Moreover, the number of criteria can be substantially larger and include environmental compatibility, required resources as well as the number of technological process stages, etc.

Selection of Available Alternatives and Their Features

As mentioned above, the available alternatives include three commonly used technologies such as chemical etching, photoelectrochemical etching and imprint lithography. Below is their brief description.

Chemical technology is instantiated by the simplicity of its process. The semiconductor is immersed in an electrolyte solution (acidic, alkaline, saline) for a significant period of time. The choice of etchants is vital since some of them can lead to surface polishing while the others account for the crystal erosion followed by the formation of nanorelief. This technology is cheap and does not require any sophisticated equipment with its technological process reduced to a few number of stages. However, it is poorly controlled and inefficient.

Photoelectrochemical etching differs from chemical etching in that a platinum plate is immersed in the electrolyte together with the semiconductor. An electric current is subsequently passed with the samples being externally illuminated. This results in the etching of defective areas and the formation of developed porous nanolayers. This technology is also simple and is marked by its process speed (from 5 to 30 minutes) as well as cost-efficiency. Electrochemical etching is more controllable compared to chemical etching since one can obtain a regular nanorelief with tailor-made properties by elaborately selecting technological conditions and parameters of the virgin crystal on the surface. Nevertheless, it should be taken into account that photoelectrochemical etching of semiconductors often evokes self-organization processes significantly affecting the controllability of the process as well as the final result.

Imprint lithography is the most controlled and efficient technology implemented as follows. A layer of organic matter is applied to the surface of the semiconductor with the subsequent alignment of the plate and the mould followed by applying a resist layer, squeezing (imprinting) the pattern and exposing the resist to ultraviolet light. The further ionic or electrochemical etching dissolves the surface according to the template pattern. However, this technology is time-consuming and requires special-purpose equipment and resources. At the same time, the resulting nanostructures have properties very close to the reference ones.

Conditional Estimation of the Available Alternatives

Technologies can be conditionally estimated according to the selected criteria using the following simple correspondence: "++" - high level, "+" - medium level, "–" - low level (Table 2.). We accept such "conditional estimators" since we are focused neither on the significance of each of the criteria nor on their corresponding interrelations.

Table 2. Compliance of the Nanostructure Synthesis Technologies with Quality Criteria

C / T	C_{eff}	C_{si}	C_t	C_{cost}
CE	-	++	+	++
PEC	+	+	++	+
IL	++	-	-	-

Subsequently, we use Table 2. in order to estimate all three technologies by adding positive estimators and subtracting negative ones, i.e., "++" is estimated as 2, "+" corresponds to 1 and "–" corresponds to (-1). The obtained relative result is displayed in Table 3.

Table 3. Conditional estimation of the Synthesis Technologies by Selected Criteria

Technology	*Relative result*
CE	4
PEC	5
IL	-1

According to such conditional estimation, photoelectrochemical etching proves to be the priority technique followed by conventional chemical etching. Imprint lithography has a negative result. In fact, both photoelectrochemical and electrochemical etchings are frequently used to create nanorelief on the surface of semiconductors. Chemical etching, in turn, is more commonly used for layer-by-layer etching or polishing whereas controlled synthesis is possible only when using lithography.

The above demonstrates that a simple conditional estimation without regard for the standardized coefficients and an elaborated estimation scale can give an erroneous result. Students should be familiarized with the disadvantages of this estimation technique subsequently comparing it with the results obtained using the hierarchy analysis method.

Selection of the Optimum Alternative Using the Hierarchy Analysis Method

Let's develop a simple hierarchical structure with one criteria level (containing four) and available alternatives (Figure 4.).

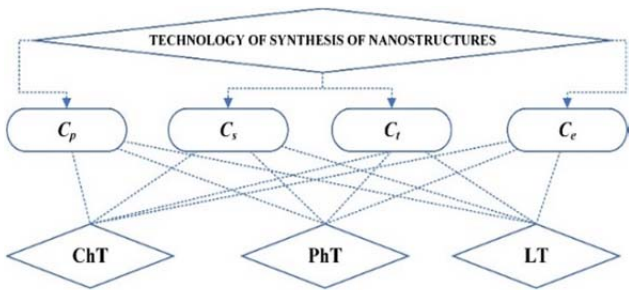

Figure 4. Hierarchical structure for selecting the optimum method for the synthesis of porous layers

As mentioned above, the best result can be obtained when using lithography. Therefore, we prioritize this technique over CE and lean toward lithography over PEC. The PEC has many points in its favour compared to the CE in terms of process efficiency.

Photoelectrochemical etching is the least time-consuming technology thus gaining absolute advantage over chemical etching and a very high advantage over lithography. In turn, IL has a significant advantage over CE in terms of this criterion.

The CE displays an absolute advantage over IL and a very high advantage over PEC in terms of implementation simplicity. Moreover, the CE unavoidably outperforms the IL in terms of efficiency whereas its advantage over the PEC is relatively moderate.

Based on the pairwise comparison of available alternatives, we can write a matrix of pairwise comparisons for different criteria levels in tabular form (Table 4.). The calculated values are given in Table 5. The maximum element in the matrix is 0.709. Therefore, imprint lithography proves to be the most significant parameter when selecting the optimum synthesis technology aimed at achieving the highest result.

Table 4. Matrix of pairwise comparisons for different criteria levels

	CE	***PEC***	***IL***
	C_{eff}		
CE	1	7	9
PEC	1/7	1	5
IL	1/9	1/5	1
	C_t		
CE	1	9	5
PEC	1/9	1	1/7
IL	1/5	7	1
	C_{si}		
CE	1	1/7	1/9
PEC	7	1	1/5
IL	9	5	1
	C_{cost}		
CE	1	1/3	$^1/_9$
PEC	3	1	$^1/_7$
IL	9	7	1

Table 5. Calculated values for eigenvectors of available alternatives

Indicator	C_{eff}	C_t	C_{si}	C_{cost}
Ws (the main eigenvector)	$\begin{pmatrix}15\\1{,}254\\8{,}2\end{pmatrix}$	$\begin{pmatrix}1{,}444\\4{,}143\\17\end{pmatrix}$	$\begin{pmatrix}1{,}254\\8{,}2\\15\end{pmatrix}$	$\begin{pmatrix}1{,}444\\4{,}143\\17\end{pmatrix}$
S (the sum of all matrix elements)	24.454	22.587	21,254	22.587
W (the approximate value of the eigenvector after standardization)	$\begin{pmatrix}0{,}613\\0{,}0513\\0{,}335\end{pmatrix}$	$\begin{pmatrix}0{,}0639\\0{,}183\\0{,}753\end{pmatrix}$	$\begin{pmatrix}0{,}0513\\0{,}335\\0{,}613\end{pmatrix}$	$\begin{pmatrix}0{,}0639\\0{,}183\\0{,}753\end{pmatrix}$
λ_{max} (the approximate value of the main eigenvector)	3.734	3.3	3.734	3,3

The next step is the hierarchical synthesis. We sequentially determine the priority vectors of the available alternatives in relation to certain criteria. Such priority vectors are computed from lower to upper levels taking into account specific interconnections between elements of different levels. This computation is performed by multiplying the corresponding vectors and matrices:

$$\begin{pmatrix}0{,}613 & 0{,}0513 & 0{,}0639 & 0{,}0639\\0{,}0513 & 0{,}335 & 0{,}183 & 0{,}183\\0{,}335 & 0{,}613 & 0{,}753 & 0{,}753\end{pmatrix}\begin{pmatrix}0{,}0337\\0{,}213\\0{,}557\\0{,}196\end{pmatrix} = \begin{pmatrix}0{,}0797017\\0{,}21088281\\0{,}7088675\end{pmatrix}$$

4. Discussion

Comparison with the conditional estimation presented in Tables 2. and 3. indicates significant discrepancies. The above clearly demonstrates the importance of pairwise comparison of each criterion as well as consideration of the weight coefficients in order to select the most suitable technology for the synthesis of nanostructures. The given example emphasizes the importance of developing one of the key professional competencies of prospective nanotechnologists, namely the mastery and profound knowledge required when seeking optimum solutions for the efficient synthesis of innovative samples of high-quality nanostructures.

It should be noted that an experienced nanotechnologist is unlikely to apply the suggested method for the synthesis of nanomaterials with the purpose and properties similar to those that they have already created. In this case, the synthesis technologies will differ significantly thus eliminating the need for a detailed analysis. This is due to the fact that experienced nanotechnologists tend to give their preference to particular technologies that have proved to be the most efficient and convenient.

Hierarchy analysis method has its own restrictions when it comes to selecting the optimum technology for the synthesis of nanomaterials, namely the need to be well versed in the nuances of technology in advance as well as the inability to predict the results.

The nanotechnology industry can sometimes limit the application of certain techniques due to a lack of equipment, personnel and materials. Therefore, selecting a suitable method is often conditional upon the available technological resources.

However, since the students are not yet aware of their future work environment and are only grasping the technologies for the synthesis of high-quality nanomaterials with tailor-made properties, mastering and applying the hierarchy analysis method is extremely important with regard to understanding the research methodology, theory and practice as well as gaining research experience.

5. Conclusion

The article considers a technique for training prospective nanotechnologists to select optimum solutions for the synthesis of innovative nanostructures samples using the analytic hierarchy process. To put that into perspective, we suggest two methods, namely the conditional estimation and hierarchy analysis. As it has been demonstrated, a simple conditional estimation is likely to provide an erroneous result while the hierarchy analysis method (HAM) proves to be a reliable and representative technique.

Hierarchy analysis is an efficient training tool as it allows for the following:

- to identify and estimate important criteria and quality indicators inherent to nanostructures, subsequently allowing the prospective experts to navigate in the features and specifics of modern nanomaterials;
- to select the optimum management decision pertaining to nanostructures synthesis thus ensuring process optimization as well as granting an economic advantage and reducing the number of errors;
- to analyse activity and predict corresponding activity results which is crucial in the work of a modern-day expert engaging in high-tech technologies with no room for an error;
- grasping this technique will allow us to make the best use of its performance potential when selecting the synthesis of nanostructures as well as to expand some other aspects of professional activity including but not limited to the investigation and identification of the most substantial properties, conceptualization of nanostructures quality level etc.

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