Intelligent System for Experimental Investigations of Optical Nanostructures

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Abstract

The issues of increasing the efficiency of experimental studies of nanostructures are considered, methods and tools for measuring and diagnosing multilayer nanostructures are analyzed, and the main research methods used in various experimental studies are given. The development of an intelligent system for experimental studies of nanostructures, consisting of a subsystem of measuring and diagnostic tools, a subsystem for measuring and generating influences, a subsystem for processing and analyzing data, a subsystem for decision making and experiment planning, a computer database and an interface, is substantiated. The structure of the intelligent system and the structure of measuring and diagnostic tools included in the subsystem of measurement and diagnostics in complex studies are given. The functions of the corresponding means of measurement and diagnostics are determined in various experiments, in combination with research methods. It is shown that the intellectualization of experimental research is achieved both by the built-in functions of intelligent measurement and diagnostic tools, and by special software developed using new information technologies, artificial intelligence based on fuzzy logic, genetic algorithm and artificial neural networks. The data obtained in the course of experimental studies and the results of the analysis allow to plan new experiments on the nanostructure.

Keywords

Nanostructure, investigation, intelligent system, measurement methods

1. Introduction

With the development of quantum electronics, the issues of studying quantum devices on nanostructures for solving the problems of creating opto- and nanoelectronic devices, such as photo- and light-emitting diodes, as well as lasers, and systems with extended functionality, i.e. in optical elements that generate, amplify, modulate, transmit and detect light radiation becoming are demands. Three-dimensional semiconductor nanostructures have unique physical properties that make further study of their properties urgent. As in all areas of technical research, in experimental studies of nanostructures, studies of electro-physical (which include electrical and photoelectric properties), physicochemical, thermo-physical (dependence of characteristics and properties on temperature) and mechanical properties of both individual layers and the entire heterostructure should be carried out, depending on the technology of its creation. In this case, electrical and optical methods of research and diagnostics, as well as structural diagnostic methods, covering probe research methods, which are non-destructive methods of control, can be used. The use of X-ray microprobe analysis methods to determine the concentration of elements or the composition of crystals is quite effective.

2. Method and materials

Note that in recent years, significant progress has been observed in the production of nanoporous materials and materials with graphene; polymer and nanocomposite materials, which requires additional research in this direction. This applies to both semiconductors and dielectric materials, which are used to create a nanostructure device [5].

There are a number of measuring complexes and installations for automating the research of semiconductor devices, for example, [6-8], the use of which makes it possible to study heterojunctions and the thermal impedance of LEDs. However, these devices and complexes are

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not universal, they do not use the capabilities of new information technologies and artificial intelligence, which make it possible to increase the accuracy and reliability of experimental studies of nanostructures by an order of magnitude.

3. Solution of the problem

Based on this, an intelligent information-measuring system is proposed for experimental studies of optoelectronic nanostructures, for studying the features and patterns of processes occurring in a nanostructure, and diagnosing the state of an already finished structure (Fig. 1).

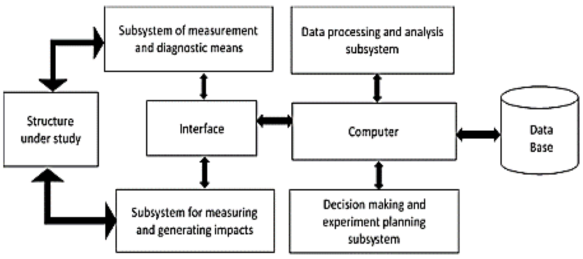

Figure 1: Structure of intelligent system

This system consists of subsystems for measuring and diagnosing, a subsystem for processing and analyzing information obtained during research and making a decision, a subsystem for measuring and generating influences, a subsystem for making a decision and planning an experiment, a computer and a database. On the basis of the data processing subsystem of experimental studies embedded in the information processing algorithms, data is filtered and smoothed, the selected mathematical model is identified, and data is prepared for the decision making subsystem. The parameters and characteristics of the studied metals, oxides and alloys, the settings of various measuring instruments and technical means of measurement and diagnostics are entered into the database.

The database management system will improve the efficiency of working with the database, which will be reflected in the timely updating of the database and the reduction in the amount of irrelevant information.

The intellectualization of the acceptance process is especially effective in the study, for example, with electron and probe microscopy and spectroscopy devices, when it is necessary to use pattern recognition methods to diagnose surface defects on each layer, and the entire structure. In this case, the most efficient way to process information is to use digital images processing. The issues of decision-making intellectualization can be solved using both intelligent measuring devices and using new information technologies, fuzzy set theory, fuzzy logic, genetic algorithms and artificial neural networks. The intelligence of the system is also ensured by the use of intelligent sensors and measuring transducers, in which the preliminary processing of measurement information is carried out with filtering and smoothing of signals, rejection of anomalous measurements, which reduces the redundancy of information entered into the system, and increases the speed and productivity of system.

The connection of experimental setups with measurement and diagnostic tools to the intelligent system is carried out through a special interface that ensures the coordination of the levels of the measured signals with the levels of logical and digital signals. The measured parameters are voltage, current, capacitance, frequency and power of the light beam, magnetic field strength. Controlled parameters: current and voltage of the substrate and the entire nanostructure, light beam power, magnetic field strength. At the same time, some parameters, namely, voltage, current and frequency, can be measured by virtual measuring instruments, which allows you to control these parameters by controlling them on the monitor. The spectral composition of substances is determined by a monochromatic device [9]. Measurement of current-voltage and capacitance-voltage characteristics is carried out to determine the electro-physical parameters of the nanostructure, and the photo conversion efficiency or sensitivity of the device or structure is determined depending on the lighting [10].

Data processing consists in their preliminary filtering and smoothing, approximation and identification of the mathematical model of the process under study, or changes in any parameter or property of the studied layer or the entire structure. In case of difficulty in obtaining a deterministic mathematical model, it is advisable to use probabilistic methods for constructing a model or artificial intelligence methods, for which an appropriate application package is developed and used. At the same time, it is necessary to consider the possibilities of simulation modeling, which increases the efficiency of the study, and, in turn, the efficiency of planning experiments to obtain the desired results. A separate task is the issues of spectral and wavelet analysis, the emission spectrum of an LED or laser, as well as a light source in the study of photodiodes. Wavelet analysis allows you to visualize spectral studies, to obtain real ranges of frequency changes in the radiation spectrum. Note that the same analysis is carried out when studying the effect of current of various frequencies and shapes on the nanostructure. Thus, spectral analysis occupies a special place among various types of research conducted with nanostructures. Another type of research is the study of the magnetic structure that makes up the nanostructure. This type of research requires careful planning of the experiment and high-precision measuring sensors of the magnetic field strength. The method of photoelectric spectroscopy is used to analyze quantum-sized nanostructures, and diffraction methods of analysis are used to study the structure of a substance. There are X-ray diffraction analysis, analysis methods with electron or neutron diffraction.

The study of a layer or structure is carried out in accordance with the instructions described in the instruction manual for the measuring equipment, adjusting the experiment plan taking into account the obtained and desired results. Display of information about the progress of experiments, about the settings of various measuring devices and installations is carried out in real time, which allows you to observe the processes under study on the monitor, compiling reports - intermediate as necessary and at the end of the planned studies, at the request of the researcher, indicating the main measured and controlled parameters. At the end of these studies, an analysis of the entire research process and the final results obtained is carried out in order to clarify the level of research and the goals achieved. In case of insufficiency of the information received, new or repeated studies are planned with doubtful data.

The data obtained in the course of experimental studies and the results of the analysis also make it possible to plan new experiments with the nanostructure by varying the number, thickness and material of the layers, as well as the exposure parameters.

The purpose and functions of this system are to increase of:

- accuracy and reliability of measurements;
- efficiency of processing the results of measurement and data analysis;
- and expansion of functionality and options;
- reliability of diagnostic procedures;
- effectiveness of experimental studies.

Based on the range of tasks solved in experimental studies and the functions of an intelligent system, the configuration and composition of the subsystem of technical means of measurement and diagnostics can be different. For a complete and comprehensive study of nanostructures, this subsystem includes the following means (Fig. 2):

- X-ray equipment for probe spectroscopy;
- thickness gauges together with high-resolution microscopy units;
- scanning electron microscope;
- electron scanning probe microscope (scanning tunneling microscope and scanning atomic force microscope);
- secondary ion mass spectrometer;
- radiation pattern meter;
- installation of measurement of surface density;
- gauges of electrical and magnetic quantities.

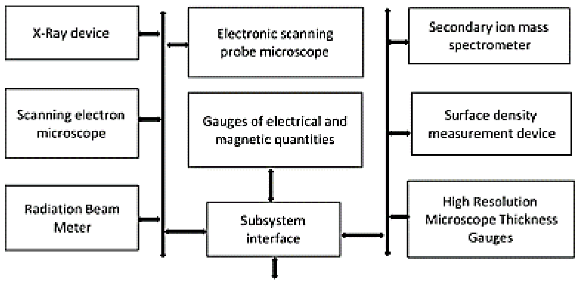

Figure 2. Measurement and diagnostics subsystem

It is advisable to build the subsystem interface on the basis of programmable logic controllers, which makes it possible to increase flexibility and speed, quickly configure the interface with various equipment. It is advisable to choose unified information exchange protocols for interfaces.

The curvature of the plates is determined by the method of wide-field panoramic interference, determining of the surface roughness - by the method of profilography and ellipsometry. The evaluation of surface roughness (roughness) at the nanoscale is carried out by probe microscopy. The orientation of the plates is determined by X-ray diffraction analysis and the chemical composition - by secondary ion-mass spectroscopy, electron microscopy, chemical analysis is carried out by photoelectron spectroscopy. The method of scattering of light, together with the study of the spectrum, is used to analyze the phase and chemical composition.

The subsystem for generating influences and measurements generates signals for changing the main parameters for each research method according to the experimental plan and affects the structure under study and issues clock signals for measuring quantities.

The algorithm for conducting, analyzing the results and planning experimental research and decision-making based on artificial intelligence with machine learning will automate some types of experimental research. In accordance with the above, the simplified algorithm can be presented in the following form (Fig. 3).

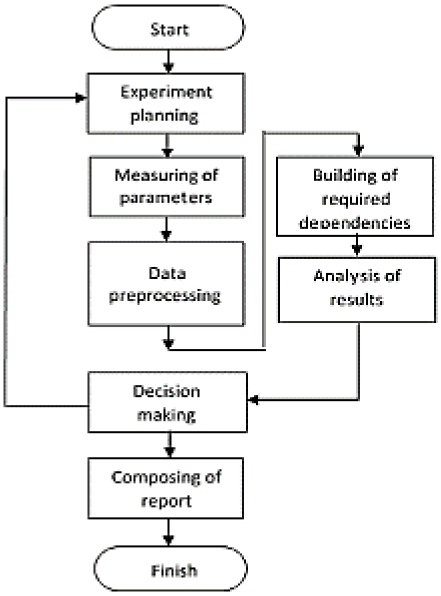

Figure 2. Block-diagram of simplified conducting and data processing algorithm of experiments

The simplified algorithm functions as follows. In accordance with the tasks and purpose of experimental studies, an experimental plan is drawn up. Further, according to the developed plan, experiments are carried out and measurements of the selected parameters are carried out. The measurement results are then pre-processed where the data is filtered, smoothed and averaged. The obtained data are used to build the necessary dependencies, characteristics and graphs. To approximate dependencies, deterministic mathematical models are used if they adequately describe the process under study, otherwise, for identification, it is necessary to use genetic algorithms or algorithms based on artificial neural networks, which makes it possible to obtain sufficiently adequate models, although they differ in the initial complexity associated with the development of more complex software. After analyzing the results of experimental studies, control is transferred to the decision-making block, where a decision is made to complete or continue the studies. If the data obtained satisfy the objectives and goals of experimental research, a research report is compiled, otherwise, new experiments are planned or a correction is made to the previous plan.

The decision block can be built on the basis of the principles of an expert system using fuzzy logic and fuzzy inference, for which fuzzy rules for conducting experiments and analyzing research results are developed and inputted in advance, and machine learning of the decision block can be provided using artificial neural networks that can also be used to identify the mathematical model of the process under study.

Thus, an intelligent system for experimental studies of nanostructures should provide the solution of the following tasks and functions:

- planning of experiments;
- development of control actions on the structure under study
- conducting experiments;
- measurement of controlled and uncontrolled parameters;
- preliminary processing of measurement results;
- choice of approximating functions for the obtained dependencies;
- identification of mathematical models and verification of their adequacy;
- determination of the fulfillment of the goals and objectives of the experiments and decision-making;
- composing of the reports on the performed experimental studies.

Experiment planning is carried out to optimize the number of experiments and increase the reliability of the results. When planning an experiment, full and fractional factorial principles can be applied. In the first of them, during the experiment, all factors influencing the process are varied, which leads to a rapid increase in the number of experiments with an increase in the number of factors, to redundancy of information. In a fractional factorial experiment, which is part of a full factorial experiment, only significant factors are used, i.e. factors whose change leads to significant changes in the target values. The choice of factors for careful planning of experimental studies is influenced by the results obtained on the basis of a preliminary theoretical analysis of the process or several experimental experiments with the structure under study.

The generation of control actions for changing the conditions for conducting experiments and influencing the properties of the nanostructure is carried out on the basis of an experimental research plan, where the limits (ranges) of changing parameters are indicated without fail.

Research reports are carefully analyzed by the relevant departments and research customers, after which, with the permission of the responsible persons, the entire report or its individual parts can be inputted into the database for further use as examples and information for the development or correction of inference rules for decision making for future research.

4. Conclusions

The study of the growth process during the preparation (growing) of crystals is important for the creation of nanostructures with the required characteristics. This problem is solved on the basis of crystal surface monitoring data. The heterostructure also contains additional layers, for example, a dielectric layer based on silicon oxide and a substrate, directly in which the remaining layers of the nanostructure are grown, which, in turn, also require research.

The interface functions in this system are quite complex, therefore, a careful approach is required to the selection and development of matching devices with various types of hardware installed in measurement and diagnostic tools, as well as in means of generating effects. A separate task is the software compatibility of these tools with other subsystems and the main software of the system. For this purpose, it is planned to develop additional software blocks that provide a solution to this problem.

The operating algorithm of the system for the conducting, analyzing of the results and planning experimental research and decision-making based on artificial intelligence with machine learning will automate some types of experimental research.

The proposed system will increase the productivity, efficiency and effectiveness of nanostructure studies in the process of creating layers and finished nanostructures.

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