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Flexible Control in Nanometrology

Gheorghe Popan and Ana Elisabeta Oros Daraban

Abstract

The unceasing development of new small products has increased constantly by introducing multiple facilities in line production, reduced life cycles of new innovative products, and high-precision techniques that require automation and robotization of the nanotechnology production processes. Classic size products are made in normal series and deal little change over the years, while in the field of nanotechnology, product life cycles were shortened significantly, and series production must adapt to the market challenges. Considering the fast changes and multiple innovations in production, we propose equipment that offers a high degree of flexibility and performance for quality products. To compensate efficiently, the fluctuations may appear in production series; a flexible control system is designed to adjust production for large number of items or for various models of processing. The control equipment dedicated to nanotechnologies developed by INCDMTM Bucharest offers solutions for automation processes adapted to various operations and for quick response occurring in nano-production. A modular special design offers flexibility during the process, handling and interoperable ones, along with the possibility of changes facilitated by software that controls the entire verification process and parameter selection for each checked item's admissibility.

Keywords: measurement system, calibrating nanotechnology, nanometrology, optical measuring system, laser measurement system, AFM control

1. Introduction and research problems

The rapid evolution in the field of technologies related to nanomanufacturing and nano-devices based on electrical, optic, magnetic, mechanic, chemical, and biological effects would allow measurements in specific length ranges involved. Moreover, the spectacular development of nanotechnology in recent years generated the development of new devices and smaller components, trends that have created the need to measure them by developing a new nanometrology field. For standard products, measurement and control systems and equipment have been created in hundreds of years, but for nano-metric components, new appropriate measurement systems must to be created quickly. In most cases the physical principle used to measure in the usual nano-production flow from a technical point of view does not correspond with normal measurement systems. Traditional measuring means have proved some technological limits in terms of accuracy because of the physical law constraints [1, 2, 3]. Furthermore, microsensors, transducers, and ultra-accurate machines must be calibrated or verified during production and, afterward, before reception at beneficiary, because it is through them that the measuring unit is transmitted to dedicated users, meaning final producers [4].

Control and measurement techniques in nanotechnologies face specific challenges at the actual incipient stage and form tolerances of the nano-products exceeding actual measurement equipments and standards, and new generation of performant electromechanical systems is required in the field of nanometrics [5, 6]. Thus, innovative devices based on new measurement principles have been used and developed. Industrial production implies increasing manufacturing speeds on the one hand and increasing accuracy of manufacturing on the other. This can be achieved by automating and robotizing both production and production control.

Different industries developed new innovative products or materials involved that currently utilize nanotechnology. The nanoscale analysis of biosystems and of specific materials started years ago (beginning of the twentieth century) when chemistry and physics allowed small-scale characterization (bacteria, fungi studies). Recent development of medicine applications, nano-characteristics of drugs or nano-surgery, has generated advanced progress in engineering building new nanoscale systems and creating new nano-technics [7].

Other areas of emerging technologies include semiconductors and optoelectronic design and production, which increase the progress of information and communication technologies (ICT). More and more positive results engaged new initiatives and contributed to develop nanotechnology applications for structures smaller than 100 nm. Actual growth of semiconductor industry exploded toward nanotechnology boost and industrial demand raised in the last few years, generating unstable economic expansion for electronic devices in term of quality.

New nanotechnologies penetrated globally in large areas, from electronics to optical devices and from new materials to biological systems, considering upgrade of specific and customized makers offering optimal and functional parameters of the new products. This is further relevant conceiving nano-systems based on optical, electronical, mechanical, and biological nano-devices [8].

In Romania and widely, we only find significant research and innovation projects for nano-systems and nanometrology reaching the TLR 3–4 level, stage that needs upscaling to TLR 6–8. Further, industrial nano-production needs calibrated applications and metrological infrastructure at nano-dimensions to be scaled up from laboratory stage to industrial systems, which follow the quality parameters of the production flow for every relevant process [9].

Evolving toward precise production, innovations are required for efficient production structure of control systems by designing them for accreditation; thus, some procedures ask for specific parameters that are necessary to be checked.

Nanoscale dimensional accuracy covers a narrow range of tolerances. Industrial systems in nano-production can't detect smaller deviations beyond the normal tolerances, and that may have unpleasant effects by damaging the production systems. Any nano-production system requires rigorous control and verification procedure based on dimensional checking; the field of nanometrology is not developed accordingly [10].

Research and innovation in nanometrology expand the number of interested scholars, who will be supporting widely new sustainable production of nano-devices, nano-systems, and nano-materials.

Industrial processes, from medical devices to aeronautics, involve a structure where process accuracy and product quality are supervised by a system of characteristic control for every landmark product, ensuring interchangeability of product parts and the functional parameters of the product [11].

Only a few organizations have integrated this kind of research; most applications are limited at laboratory findings. The main barrier of using nanotechnology control at large industrial scale is the lack of specific infrastructure; for that reason this study proposes some solutions (**Figure 1**) [8–10].

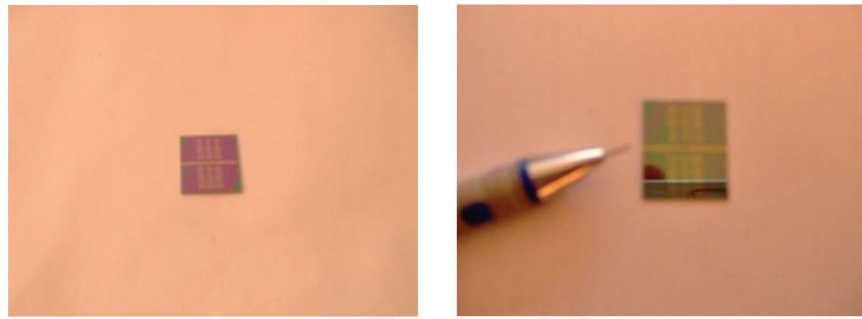


Figure 1.
Nano-electronics devices.

The equipment for nanometrology further presented is based on the experience of more than 30 years in research and didactic activity of the main author in the field of measuring devices and dimensional control systems. Activity in the field began with the design of control systems and devices from precision mechanics, with laser measuring and controlling equipment (laser probe heads, laser beam-scanning measuring systems, 3D cordless measuring machines, laser head, laser camshaft measuring equipment, laser calibration of coordinate measuring machines, and precision tool machines) [12].

The advantages of studying and realizing these systems are the basis for the next research and innovative solutions for nano-industries in terms of quality and precise manufacturing. The disadvantages are that systems and benchmarks to be verified in nanotechnological production are not palpable and in most cases are easily deformable and only distinguishable by a microscope. The transition from metrology to nanometrology required a new approach. Touch contact systems can no longer be used; the appropriate optical measurement principle—video inspection, laser scanning, and atomic force microscope (AFM) testing—must be approached.

The equipment is designed and developed by a multidisciplinary team from INCDMTM (National Institute for Research Development for Mechatronics and Measurement Technique) in Bucharest. The equipment is mainly driven by the need to control the production flow of a recognized mobile phone company based in Romania. Meanwhile, the mobile phone company ended its tax-free period and relocated its production from Romania to another country.

The chapter is structured according to primarily an introduction which highlighted the state of the art of this theme and secondly to describing the main parts of the equipment structure (experimental model). This includes Subchapter 2.1 that shows the optoelectronic control system including the charge-coupled device (CCD) camera, with examples of controllable nano-sensors; Subchapter 2.2 presents briefly the following control station with the laser control system; and then in Subchapter 2.3, the control station with the atomic force microscope (AFM) is shown, followed by a brief conclusion and direction for future research.

2. Experimental model

The experimental model presented in this paper for an innovative control and calibration equipment is built based on rotary feeding systems including table supports which are installed very precisely holding the nano-devices that need to be verified and calibrated. The equipment design allows calibration for a series of electronic nano-devices, bio-nano-devices, nano-materials, nano-sensors, or other nano-devices (**Figure 2**).



Figure 2.
Variety of Nano-devices necessary to be verified.

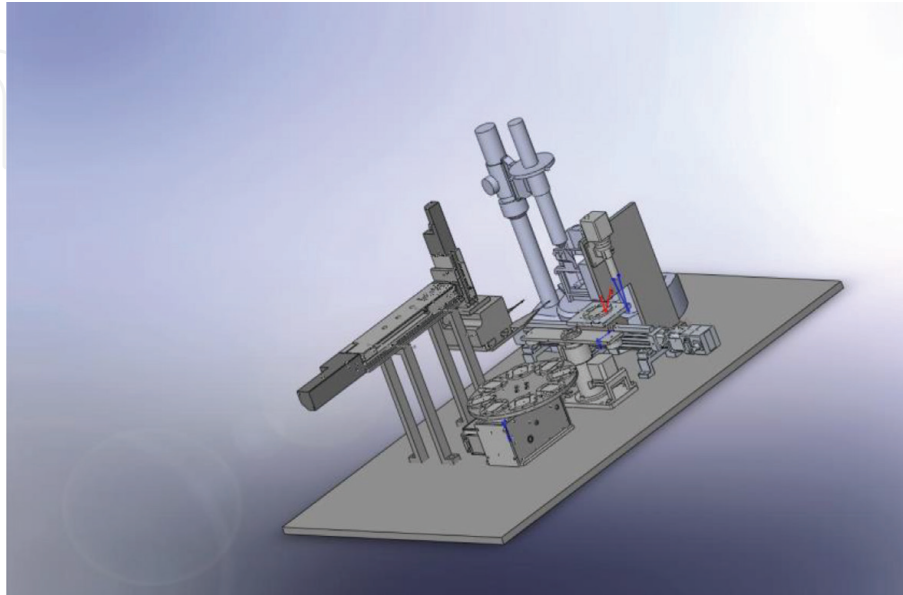


Figure 3.
Optoelectronic measuring and calibration system assisted by laser and AFM control.

The very thin nano-device calibration requires dedicated operational procedure for handling, and it is using support parts manipulated by a precision linear displacement system. These systems transfer the nano-devices by specialized automatic options (robot) to different precision measurement systems—optoelectronic, laser, or AFM—for calibration [3].

As shown in **Figure 3**, the equipment comprises a rotary feeding system, on top of which are placed eight support tables. On each support table, there is a specific plate support where nano-devices are introduced to follow the calibration procedure.

Experimental equipment includes mechanical, optical, and optoelectronic sub-ensembles, the optoelectronic measurement sub-ensembles, and the algorithms related to (real time) measurement system data acquisition, data processing, and measurement protocol presentation.

Control equipment (**Figure 4**) uses a rotary handling system including a feeding robot manipulator, a precision linear moving system, an optical measuring system, a laser measuring system, and a measuring system equipped with an atomic force microscope (AFM) [3].

The technical features of this experimental model ensure the following precision by:

- Displacement accuracy of the ultra-accurate-controlled linear positioning systems, 0.2 nm
- Laser measurement resolution, 1 nm
- AFM characterization resolution, less than 0.5 nm
- Optoelectronic measurement resolution, 10 nm

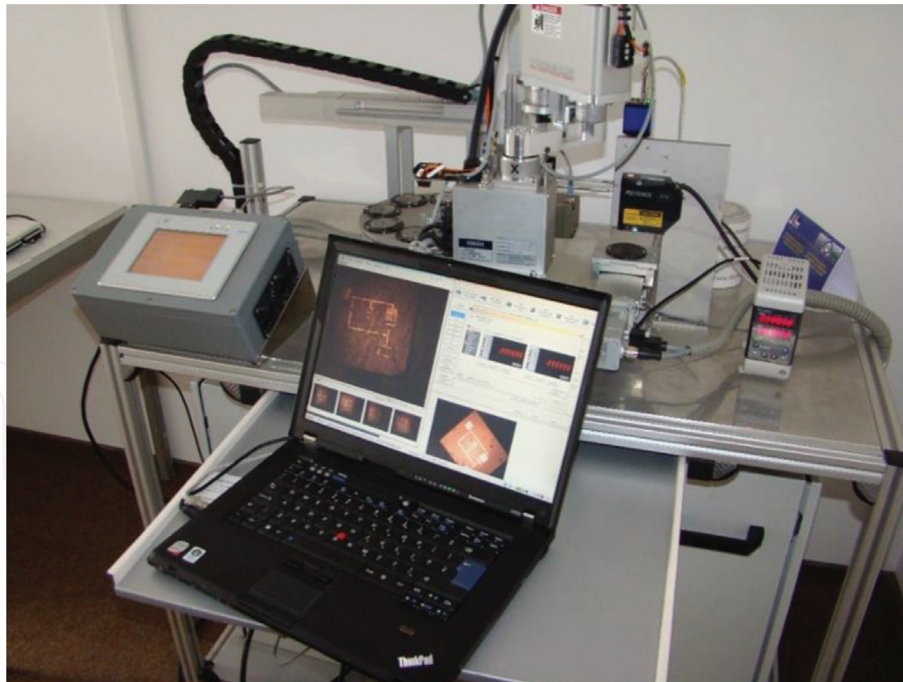


Figure 4.
The experimental equipment model.

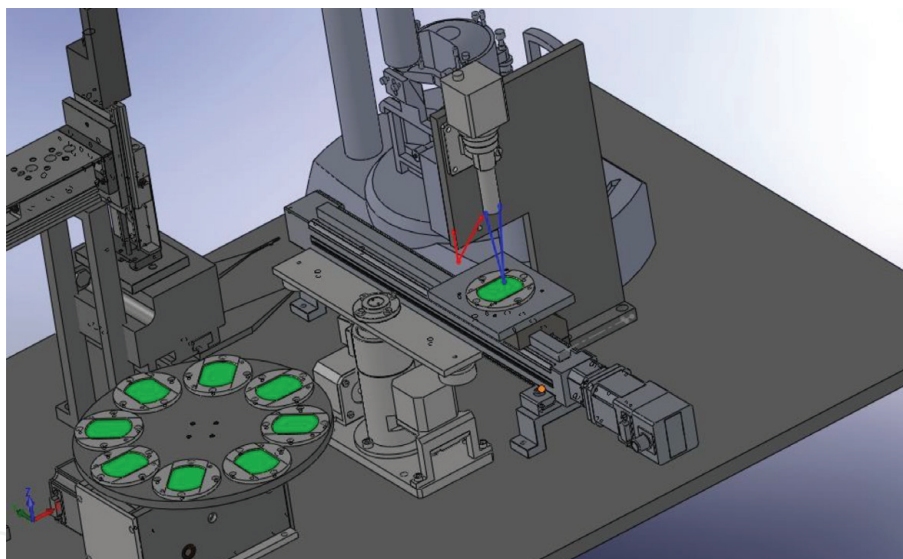


Figure 5.
Optoelectronic control.

Calibration procedure secures the nano-device optimal positioning in the support dedicated plate, which is precisely fixed on the support table from the rotary feeding system by computer coordination and transfer manipulator, which allows adjustments of the table during the precision displacement. For measuring operations with an AFM, a special feeding robot is used in order to keep accurate calibration characteristics. Dedicated computer programming procedure of the calibration system decides if the device is accepted (qualifying as good) continuing the production flow or is rejected (is not respecting the quality required) to scrap boxes (**Figure 5**).

The nanotechnological process can be adjusted using this equipment by programming automatic calibration for one, two, or three posts from eight available table supports [13]. The control software is versatile ordering automatic calibration process or manually controlled by a computer system or using touch screen applications.

The equipment developed in research institute INCDMTM is equipped to perform the flow control by means of three specialized systems:

- Optoelectronic control (microscope with CCD camera)
- Laser control
- AFM control

In this chapter the integrated control processes for nano-production flow using these three dedicated systems are presented summarily.

2.1 Optoelectronic control (microscope with CCD camera)

This testing and controlling method permits to check up the quality and cohesion of different nano-devices: semiconductor devices (SMD discrete components), microelectronic circuits, micromachined circuits, printed microcircuits, microsensors, and transducers. The optoelectronic control method using CCD camera may be adopted for finding defects from handling, assembling, or encapsulating all types of devices listed above [3] (**Figure 6**).

The equipment used in this control process must be able to demonstrate the quality conditions of the devices mentioned in accordance with the requirements envisaged in the product design.

Equipment should include optics (optical microscope) with a magnification range of 1.5–20 X with a view area accessible and large enough for determination of details. The control procedure sets up the devices that will be examined by producers at established magnifications ranging from 1.5 to 20 X. Measurements of dimensions (length/width/diameter) will be made using the order of the same range of magnification that provide good accuracy of measurements.

The dimensional measurements with optoelectronic microscope are ranked (width, length routes, or contacts) in the range of 10–2000 μm , and measurement resolution is 10 nm. The system offers rigorous linear movement of the sample nano-device based on two perpendicular directions at a distance of at least 5 mm (matching the test plan). In this case, measuring resolution should be less than 100 nm (**Figure 7**).

Applications that require the optical control are verification of integrated circuits, verification of printed microcircuits, and verification of microsensors based on amorphous magnetic materials.

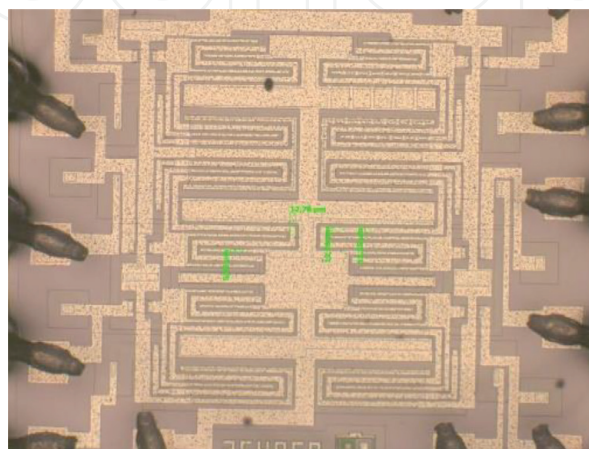


Figure 6.
Integrated circuit.

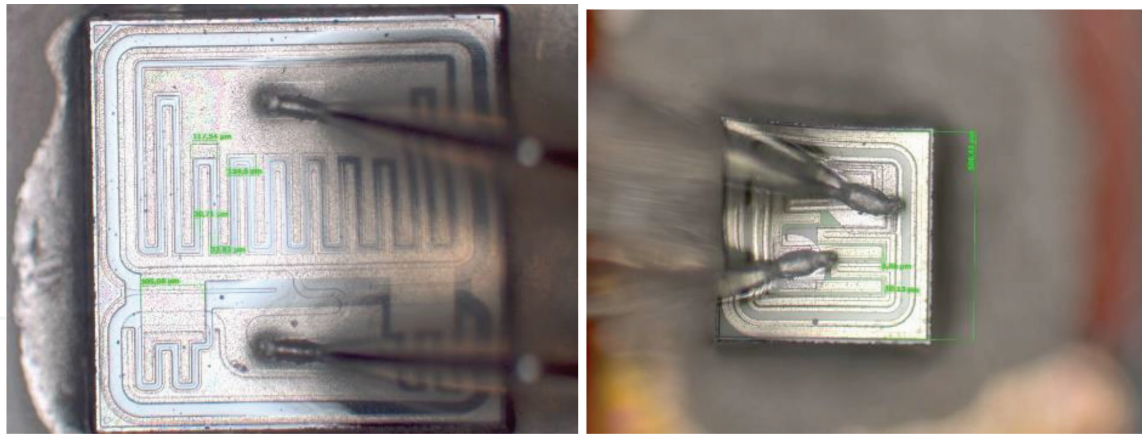


Figure 7.
Microprocessed circuits.

Some examples of the optoelectronic control applications in microelectronic circuits, micromachined circuits, printed microcircuits, and microsensors are shown (**Figures 8–13**).

Verification of integrated circuit (**Figures 8 and 9**) procedure includes:

- Verification of routes and establishing dimensional variations from the geometry of the proposed design by comparing with a theoretical form
- Verification of junctions and contacts
- Verification of profiles

Verification of printed microcircuit (**Figures 10 and 11**) procedure includes:

- Controlling the framing of deviations from the theoretical geometric shape of a circuit within the prescribed limit
- Control of circuit breaks
- Control of the geometric shape of the circuit
- Control of the presence and correct positioning of the components on the circuit
- Dimensional component control

Verification of microsensors based on amorphous magnetic material (**Figures 12 and 13**) procedure includes:

- Dimensional sensor control.
- Control of each sensor component.
- Control the correct positioning for each sensor on the circuit.
- Control the alignment of each sensor in the circuit.

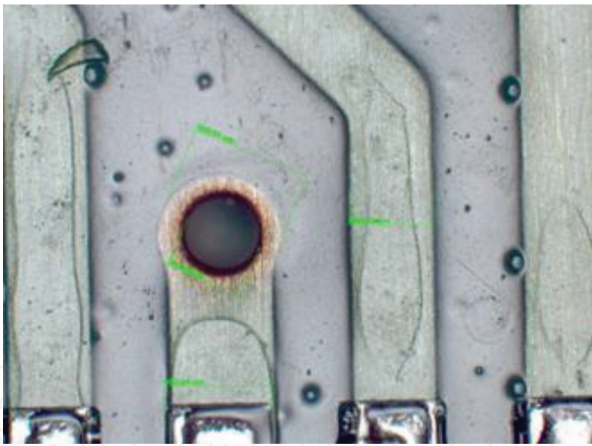


Figure 8.
Microelectronic circuits.

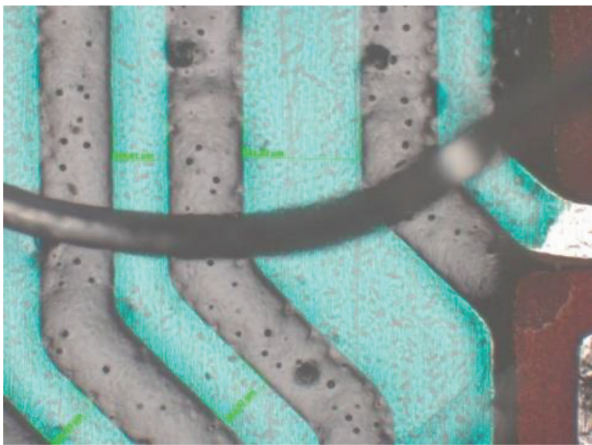


Figure 9.
Micro-imprinted circuits.

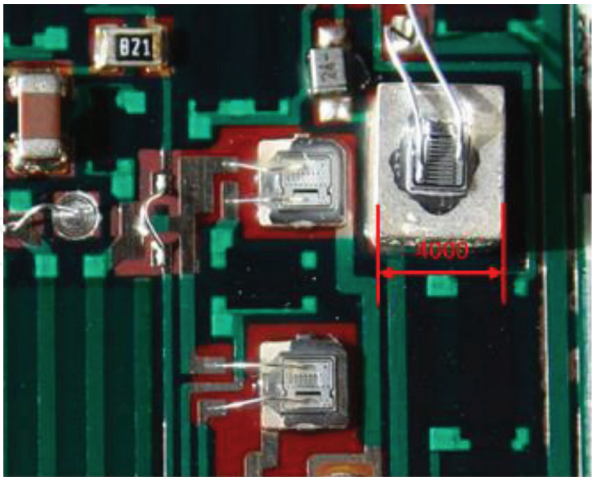


Figure 10.
Microcircuits.

2.2 Laser control

Laser measurement technologies gradually developed using multiple measurement principles that allow a large control flexibility and applicability for measurement and checking procedures.

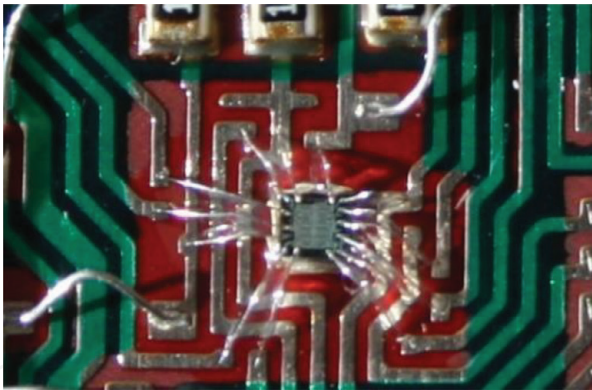


Figure 11.
Microcircuit.

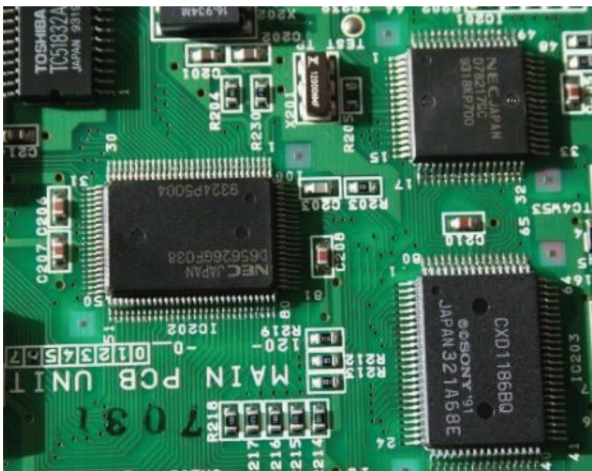


Figure 12.
Cable routes and metal-plated holes.

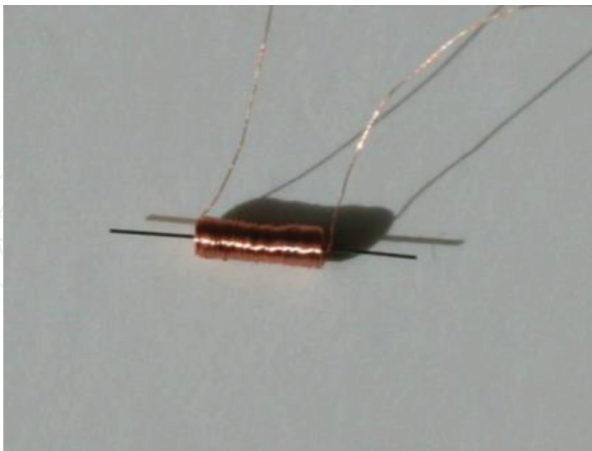


Figure 13.
Inductive sensor.

Laser telemetry measurement principle offers a great variability of distance measuring systems up to kilometer lengths. The INCDMTM center developed applications to measure distance by telemetry satellites during the formation flying useful to maintain and adjust flying positioning. This application allows monitoring of distance length between satellites, and it controls trajectory of each satellite for keeping formation flying.

Interferometry principle is used for measurement covering distances of 80–120 meters and allows high resolution up to 0.01 nm. With a large experience in the development of checking and measurement applications for sensors, transducers, coordinate measuring machines, and precise CNC machines, we proposed to use the interferometry principle for nanotechnology processes where very precise displacements in a network system can be supervised with specific sensors. Laser triangulation is an accurate measurement principle with resolution of 1 nm. This method uses measurement referential to a point for distance and object presence determinations or referential to a line covering 3D forms and a profile dimension.

The new equipment designed for very precise measurement within time checking methods applies triangulation principle. Nevertheless our institute developed measuring systems using triangulation method 30 years ago [1]; in this case to assemble this measuring equipment on the nano-production flow, we acquired some measuring systems from a specialized company.

The purpose of using this method of control is to check the quality conditions of the semiconductor devices (discrete component-type SMD) of microsensors and transducers (e.g., control surfaces, movement control, control distance/size, position control, etc.).

The equipment used in this control must be able to demonstrate the quality conditions of the devices mentioned in accordance with the requirements envisaged in the design. It should include laser equipment and devices enabling precision movements on three axes (nano-positioning stage).

The measuring principle is the method of triangulation, having a measuring range of 5 mm, measurement resolution of 1 nm, and laser measurement resolution of 1 nm.

The value of the dimensions (width/length/height of routes, etc.) that can be checked is in the range 1–2000 μm . The system allows linear movement of the sample in three directions perpendicular to distances of at least 5 mm with nanometer precision. The precise positioning table is fixed in the laser calibration position as shown in **Figure 14**.

One of the applications appropriate for using laser-based measuring method is verification of integrated circuits, procedure that includes:

- Verification of routes and dimensional variations of the geometry identified to the proposed design by comparing with a theoretical form
- Verification of junctions and contacts
- Verification of profiles

Some examples of electronic microcircuits where laser control is applicable are shown in **Figures 15–17**. First, one control application defined by triangulation method for measuring and verification of the profile, positioning, and present splice of a pin in the integrated circuit is presented in **Figure 15**.

In microcircuit manufacturing, one important issue raised by specialists is the presence and correct checking position of each specific component to ensure the designed function of integrated circuits. This checking is presented in **Figure 16(a)** using a Keyence scanner. Continuous trends of minimizing the characteristic dimensions in integrated circuits and the rapid multiplication of functions determined for the same products lead to specialized very fine and narrow circuits' paths. Each circuit's path must be produced respecting some

rigorous requirements: minimum dimensions, distance between two of the closed paths, and the transversal profile of each path line. If the checking of circuit's form and the correspondence with theoretical design of the final product is realized with optoelectronic methods using video inspection, the verification of integrated circuit parameters is made by laser triangulation as shown in **Figure 16(b)**.

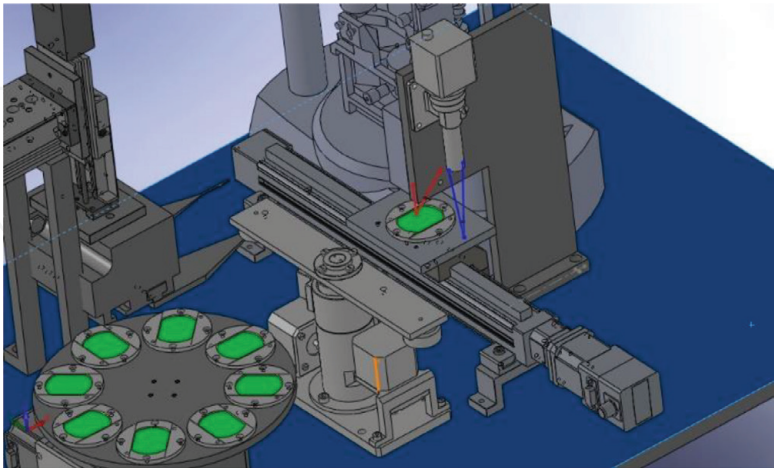


Figure 14.
Calibration with laser.

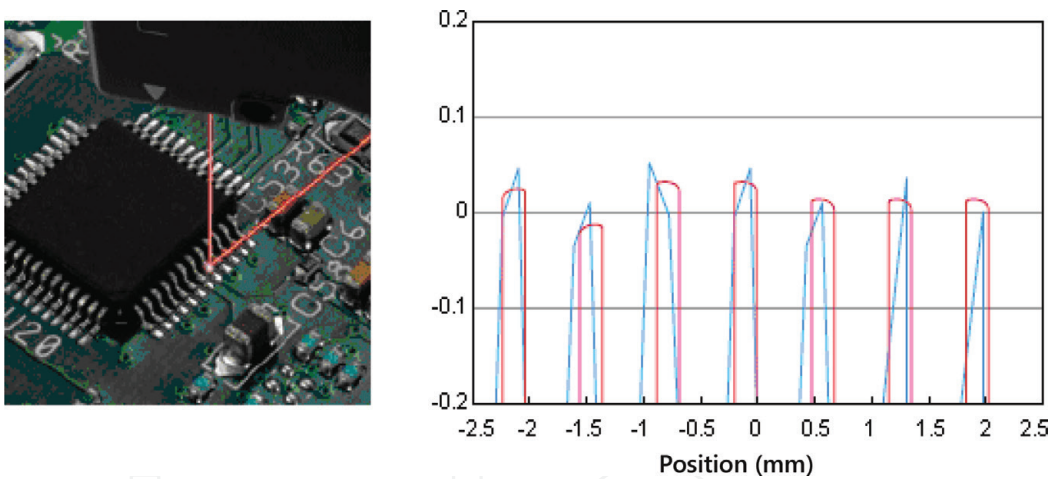


Figure 15.
Verification of the profile of pins for an integrated circuit.

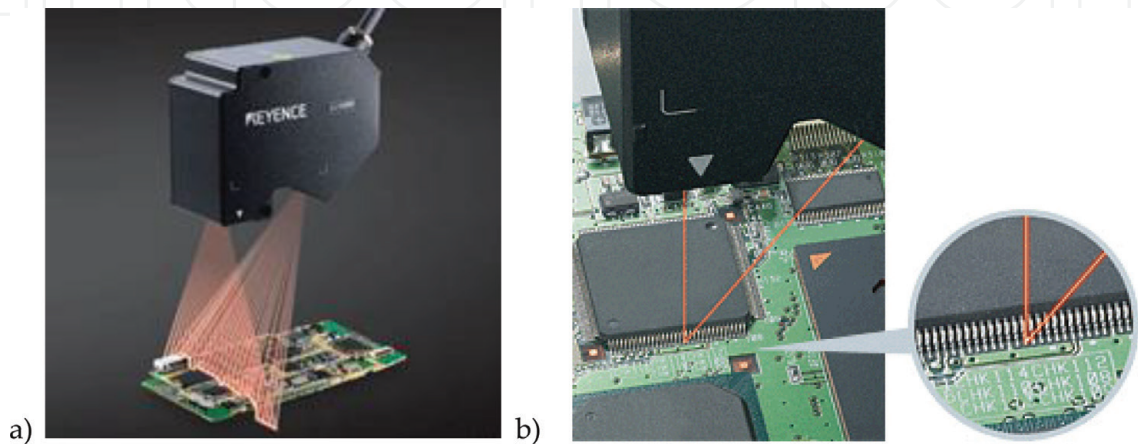


Figure 16.
Verification of the profile of microcircuits (a) and integrated circuits (b).

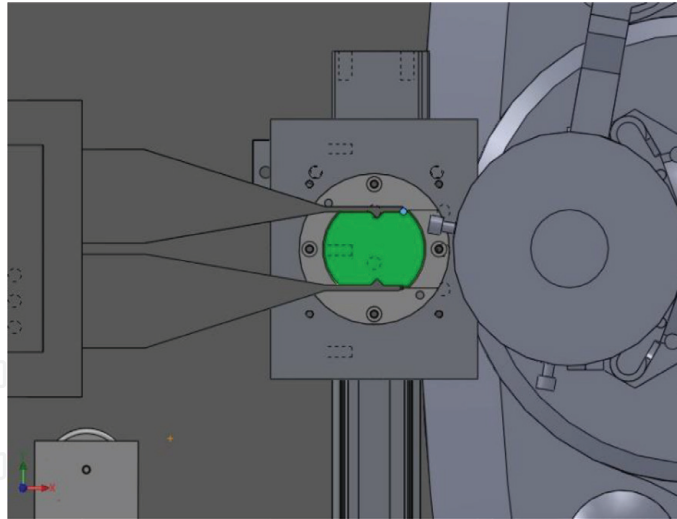


Figure 17.
Gripper clamps up the nano-device support.

2.3 AFM control

One of the problematic issues in the nano-production line control is the automatic maneuver of nano-devices. To protect nano-devices (microcircuits) during checking operations, there are specific item supports used with automatic precise displacement. Therefore, considering the nano-device control procedures, all parameters settled for measurement can be easily provided in each control point of the new equipment (optical, laser, and especially for atomic force microscope, AFM, characterization).

The purpose of using this AFM control method for nano-device testing and inspection plays an important role, and it is appropriate to check and to keep right conditions of integrity and quality of porous alumina membranes (alumina template) having pore sizes included in the nanometer range.

This control method can be used for inspecting defects that may result from the production (manufacturing industry), handling, or assembly of alumina membranes [9]. Control equipment used must be able to demonstrate the quality conditions of the porous alumina membranes in accordance with the requirements envisaged by product theoretical design. Control equipment is endowed with specialized systems that include an AFM.

The method of verification, control, and calibration includes the following procedure characteristics:

- The device must provide noncontact imaging solutions for nanoscale metrology.
- The scanning range on XY (sample plan) must be at least $100 \times 100 \mu\text{m}$.
- The scanning range on Z must be at least $25 \mu\text{m}$.
- The values of dimensions (width/length, diameter pores, etc.) that can be checked are in the range of 1–500 nm.
- The system allows motorized sample stage in three directions, at a distance of at least 5 mm.
- The measuring resolution must be higher than 0.5 nm.

Applicable for AFM control are porous alumina membranes used for obtaining nanowires via the electrode position process, and the procedure includes:

- Verification of the dimensional pore width and of the geometry of the proposed design, compared with theoretical form.
- Verification of membrane integrity.
- Verification of profiles.

Checking and control method using AFM is described summarily as follows: nano-devices are positioned on the support plate which is useful for automatic maneuver. Maneuver operations are driven by a robot that has a clapping system for interoperation displacements of support plates (**Figure 17**).

Before automatic operation offsets, it is required to set up the measuring head of AFM, which is equipped with a special support fixed on the adjustment unit of this head. The special support must be provided with guidance systems for support plate corresponding to each nano-device that must be calibrated. Adaptation of AFM measuring head position is settled following two rectangular directions using two fine-pitch screws that allow micron precise positioning of the measuring head referential to laser beam. Setting up of detection systems is performed by using control software program.

Automatic feeding of support plates with nano-devices is completed by a precise robot using a special gripper with fine claw clamps that hold and fix the support plates with nano-device in specific hole. Gripper form allows maneuver and fixing of nano-device support compatible with the guiding system of the special support from AFM measuring head.

One important issue regarding AFM operation is the laser beam alignment into the cantilever. For nano-device precise positioning for calibration procedure, a universal measuring head was selected. The laser beam alignment is realized by joist displacement in cantilever in relation to the beam spot.

The gripper clamps up the support table with the calibration nano-device, and it is built to introduce the nano-device fixed on its support plate ready to be verified directly in the AFM socket without protection cap removal (**Figure 18**). This automatic process using AFM control admits time-saving and more productivity.

The robot lifts the support with the nano-device that must be calibrated to the height of the positioning socket of the AFM and introduces that support in the right position (**Figures 18 and 19**).

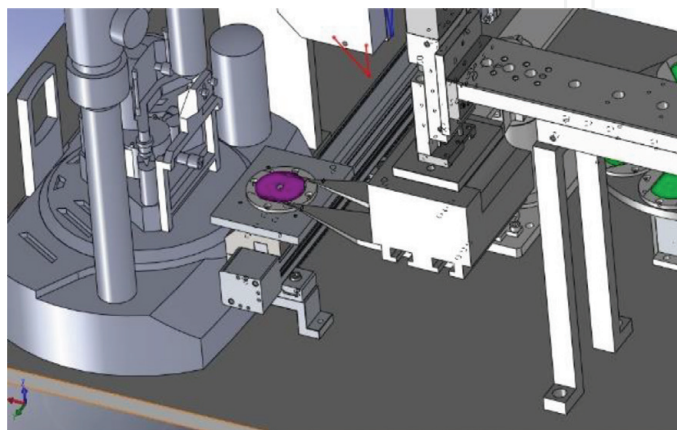


Figure 18.
Robot lifting nano-device related with AFM positioning socket.

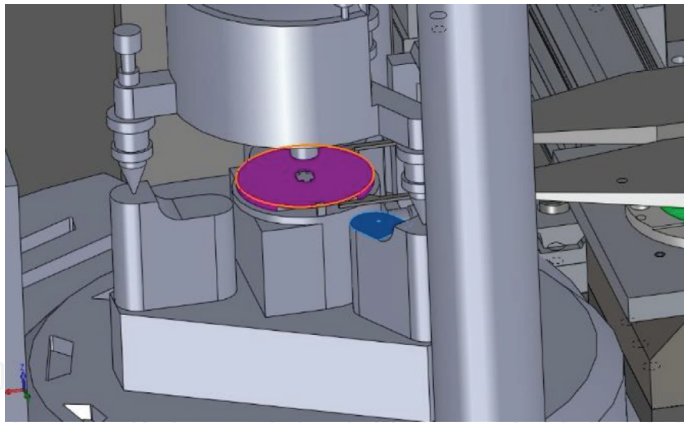


Figure 19.
Robot positioning nano-device support plate in the AFM socket.

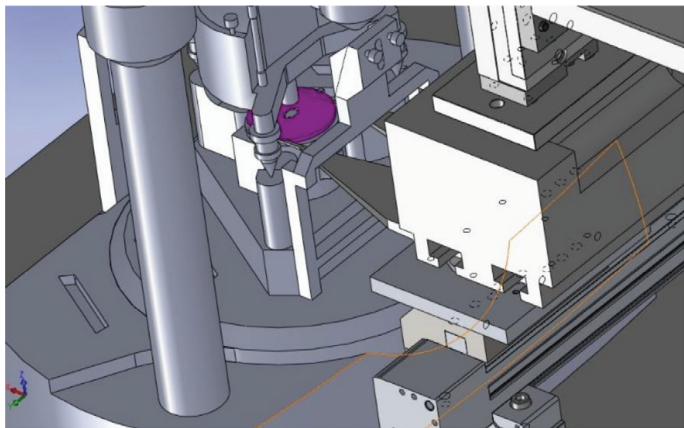


Figure 20.
Robotic performance of AFM calibration.

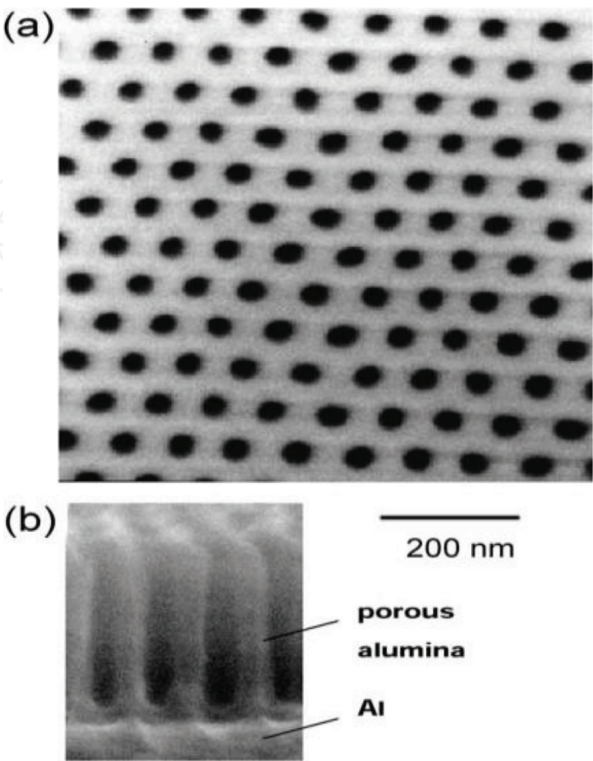


Figure 21.
Porous alumina membranes with pore diameters at nanoscale (SEM image) (a) top view and (b) lateral view.

The robot clamps off the gripper and takes down the support with the device that needs to be calibrated, and the AFM catches and holds the nano-device in the calibration position (**Figure 20**).

Control and checking technology defines if the verification is done in each checking position or only in a few checking positions and ensures the monitoring of settled characteristics important to be verified in every checking position. After every finalized checking operation, the equipment decides if the nano-device is within the tolerance limits and if it is accepted or not. If a specific characteristic of every nano-device is not corresponding within the settled limits of the technology that is designated by the measurement program, the feeding robot receives the command REBUT in every checking position, and the nano-device is eliminated from the production flow [13]. If the nano-device is accepted according to settled limits for each checking position, the robot receives the command GOOD, and the nano-device is introduced ensuing further into production flow.

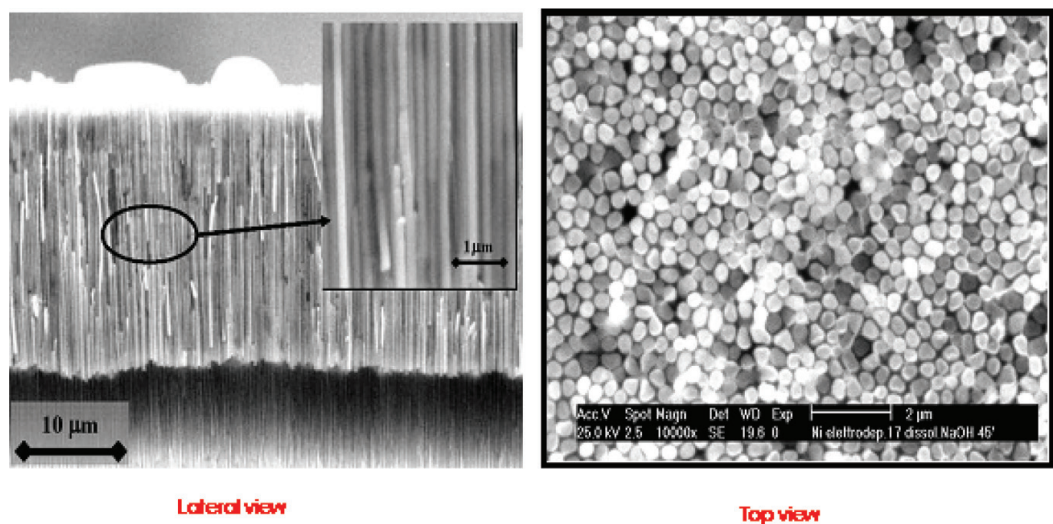


Figure 22.
Nanowires obtained through the process of nano-disposition in porous alumina membranes (SEM images).

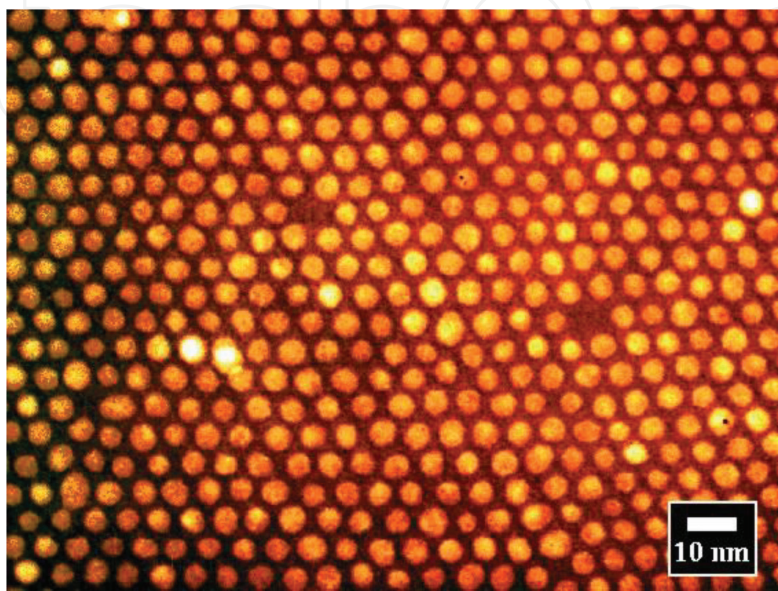


Figure 23.
Nanowires in the porous alumina membrane (AFM image).

Some relevant pictures present examples of AFM control applicability to porous alumina membranes where pore diameters are in the range of nanometers (**Figures 21–23**).

The images from **Figures 21–23** are achieved in the National Institute of Research and Development for Technical Physics, Iasi, Romania, during the collaborative research using scanning electron microscope (SEM) and AFM. These applications are demonstrative for AFM characterization and are dedicated for very precise control and checking processes in the nano-production flow.

3. Conclusions and future research

The experimental model permits optical, laser, and AFM microscopic verifications of realized nano-devices in order to correct possible production errors [3, 6, 12, 13]; thus, it allows nano-production calibration and automatic selection of rebuttal during flow processes for dedicated dimensional control in range from less than 1 nm up to micrometers or millimeters.

Future research will aim at the development of detailed technologies for various applications in nano-device production field that need to be calibrated covering all ranges of electronic nano-devices, optical nano-devices, biological nano-devices, nano-materials, and nano-sensors.

To evolve from laboratory stage to nanotechnology production lines, more research and innovations may allow over passing the actual barriers:

- Traditional measurement techniques used for normal dimensional characterization cannot be applied to nano-structures.
- Special rules and standards must be introduced for nano-structures and nano-material characterization reducing errors in inspection and quality checking procedures.
- More innovative equipments must be projected in order to solve the mentioned issues.
- Different specific studies for new equipments for control production regarding nano-structure proprieties should promote reproducible production of nano-structures and nano-materials.

Nanometrology opens opportunity creation of international standards and equipments for calibration of the products and equipments used in industrial production and offers more chances of new scientific discoveries regarding innovative commercial products.

The future development of nanotechnology cannot be achieved without progress in ensuring a well-controlled, stable production carrying dimensional control and in terms of other quality characteristics. This depends both on the strategy of each area of development and especially on the joint development of the nanotechnology field. First, research should be coordinated and developed in collaboration with companies, and secondly research for standardization in the field of nanometrology must be promoted by government programs. Efforts need to be united between those with common concerns for the progress of the nanotechnologies in precise industry.

For unitary development and interchangeable products, rules and standards need to be created at European and international status both for the acceptance of

production and for systematization of products and components at the nanoscale. For large-scale production of nanotechnology products, equipments must be developed for both industrial production and production control. In order to ensure stable production, international rules must be developed and immersed for calibration of production flow and for calibration of control equipment production. Another issue that needs to be considered is that of environmental production conditions. We need to rethink environmental standards for this type of production. The old classification and standardization of clean rooms no longer correspond, and it is necessary to improve the clean room technical standards and add specific parameters. At the atomic force microscope (AFM), the measured parameter value is drastically influenced by its position relative to the air circulation system, noise, and vibration not only of temperature and humidity.

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