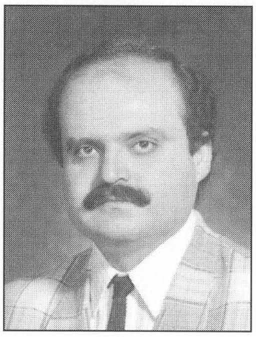
*) Od redakcji

Nawiązując do referatu wygłoszonego na sesji plenarnej KONGRESU KM-2004 poniżej publikujemy krótką charakterystykę Prof. H. Osanny. Profesor od wielu lat współpracuje z polskim środowiskiem metrologicznym uczestnicząc m. in. w pracach komitetów naukowych Kongresów Metrologi w 1998 w Gdańsku, w 2001 w Warszawie oraz we wrześniu 2001 we Wrocławiu. Ponadto brał udział w Międzynarodowej Konferencji Współrzędnościowa Technika Pomiarowa organizowanej co dwa lata przez Akademię Techniczno-Humanistyczną w Bielsku Białej oraz cyklicznej Konferencji Metrologia w Technikach Wytwarzania Maszyn. Profesor jest częstym i mile widzianym gościem w Polsce. Prof. P.H. Osanna współpracuje m.in. z Politechniką Świętokrzyską (prof. Stanisławem Adamczakiem), z Politechniką Warszawską (dr inż. Zbigniewem Humiennym) oraz z Akademią Techniczno-Humanistyczną (dr. inż. Władysławem Jakubcem) w Bielsku Białej. Owocem tej współpracy jest między innym monografia Specyfikacje Geometrii Wyrobów (GPS) – podręcznik europejski, która w październiku 2004 została opublikowana przez WNT.

Ali AFJEHI-SADAT, Herbert OSANNA, Numan M. DURAKBASA
DEPARTMENT FOR INTERCHANGEABLE MANUFACTURING AND INDUSTRIAL METROLOGY

From Nanometrology to Picometrology – Metrology for Human Life and Technical Development in the 21st Century



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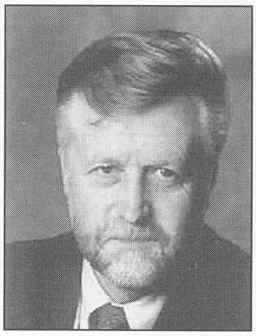

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Abstract

In this article the importance of nanometrology and nanotechnology in general for scientific research and especially for production engineering is described and particularly the influence on technical development, high precision manufacturing but also for circumstancies of human life is demonstrated. High accuracy measurement technique and metrology must be given a key role in modern production environment. Essential contributions to increase the quality of products and the productive power of industrial plants can be reached through the aimed application of nanometrology.

Streszczenie

Przedstawiono podstawowe znaczenie nanometrologi i nanotechnologii w badaniach naukowych koncentrując się przede wszystkim na inżynierii produkcji. Podkreślono wpływ nanometrologii i nanotechnologii w na rozwój techniczny, wytwarzanie o wysokiej dokładności jak również ich znaczenie w życiu człowieka. Techniki pomiarowe o wysokiej dokładności i metrologia powinny odgrywać kluczową rolę w warunkach nowoczesnej produkcji. Dzięki zastosowaniom nanometrologii można uzyskać znaczący wzrost jakości wyrobów i zdolności produkcyjnych.

Keywords: nanometrology, nanotechnology, precision manufacturing, measurement technique, quality management, precision engineering

1. Introductory Remarks – Metrology in Precision Engineering

Increases of quality of technical parts and whole products are not to be joined of course exclusively with increase of accuracy but correlation is given up to a certain extent, particularly if the technical development during the 20th century is taken into consideration [1]. This trend develops presently continuously further on because of the development from microtechnology to nanotechnology, which means particularly special metrologies and production methods for the realization of manufacturing accuracies in the nanometric range [2]. As the tolerances of workpieces and their features decrease the interaction and correlation between dimensional tolerances and surface finish becomes more important [3].

Extremely high accuracy demands deposit presently already at highly developed instruments for everyday use as there are

- video cassette recorders,
- CD-players,

- mobile telephones,
- air bags,
- fax and copying machines, further on the
- sensor technique in automotive engineering and even if we think on
- one-hand mixing taps for home appliance which demand ultra precision tolerances.

The trend in instrumentation and metrology was already developing in the electronics industry where the drive was towards miniaturization for higher packing densities and faster switching. As a result, highly controllable and stable processes such as lithography were introduced. This meant a need arose for the very accurate positioning of specimens. In turn this resulted in an interest in miniature actuators and motors and accurate slideways for which new technologies have required development. In particular new materials and thin film research were pre-eminent. As well as in electronics and manufacture, new developments on the nanoscale are taking place in the fields of biology and chemistry. In terms of disciplines, therefore, nanotechnology encompasses more than engineering.

2. Development and State-of-the-art in Precision Metrology

Since 1970 we see increasing importance of modern metrology as means to control industrial manufacturing and the quality of all kinds of products and processes. At the same time precision engineering developed as important trend in instrumentation and metrology. Optical and electronic methods are preferred tools in intelligent production plants. Their efficient use and correct calibration are crucial requirements for quality management in this production environment.

To achieve surface finishes and part tolerances in the submicrometer and nanometer level it is necessary to incorporate very sophisticated instrumentation and metrology into the design. This development started in the electronics industry but micro miniaturisation is also now of high priority for mechanical engineering.

Besides microtechnology since about 1975 we speak about nanotechnology. That term "Nanotechnology" was introduced by Taniguchi to describe manufacture to finishes and tolerances in the nanometer scale [4]. Extrapolating the specifications from existing and past machine tools, such as precision lathes and grinders, to the new generation of machine tools it was conducted quite correctly that before 2000 accuracies of between 100 nm and 1 nm would be needed to cater for the needs of industry (Figure 1). Taniguchi was too pessimistic for this has been already state-of-the-art at about 1995 [5]. This was and still is based on the development and application of high precision manufacturing processes and by the application of high precision metrology of apart conventional methods.

In principal nanotechnology is the meeting point at the atomic scale of chemistry, physics, biology, and engineering. Because nanotechnology in name at least started in engineering it is probably most informative to follow and investigate the subject in this discipline.

Developing from the need to machine more accurately as demands grew in the last thirty years came new methods of fabrication with different materials. Hand by hand with this development came the need to make very accurate machine constructions and to miniaturise sensors and actuators to enable the non-intrusive ultra precise control of instruments and production equipment. Also special demand for quality management is in the point of view in this field.

This trend to increase the accuracy is in line with the development that has been already pointed out by 1960 [1] showing the continuation starting at the beginning of 20th century which is still going on [6] and leads us directly to nano and picotechnology.

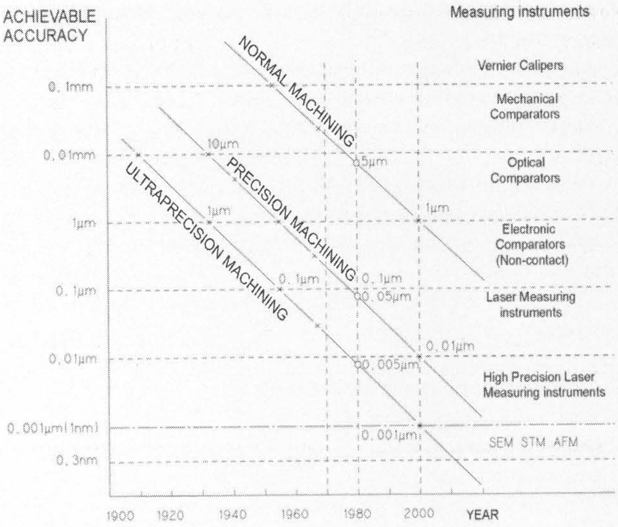


Figure 1: Development of dimensional metrology and achievable manufacturing accuracy

3. Developments and Requirements on Instrumentation in Nanotechnology

Because nanotechnology in name at least started in engineering, it is probably most informative to follow and investigate the growth of subject in this discipline. Developing from the need to machine more accurately as demands grew for example in the fields of compact discs, gyroscopes etc., new methods of fabrication came with different materials. Together with these applications came the need to make smaller sensors and actuators to enable the non-intrusive control of instruments and machines.

In engineering applications, 90 % of transducers are concerned with the measurement of displacement, position or their derivatives such as strain, pressure and acceleration. This has resulted in a mechanical micro world, which has emerged from the technology developed for integrated circuits. Already many small mechanisms are being made, including miniature motors of submicrometer dimensions. Highly reliable accelerometers are already in use. These devices are fabricated on silicon substrates using extensions of such integrated circuit manufacturing processes as photolithography, thin film deposition and the like. Micromotors and articulations are more ambitious but are developed in many parts of the world.

Instrumentation has been developed to explore and measure structure properties down at the atomic level. In engineering they have usually been involved with looking at surface topography and boundaries of one sort or another. This requirement goes far beyond the original concept of Geometrical Product Specification and Verification and of the performance of a machine tool or attainable a surface texture on a component.

The production of very precise components goes hand in hand with the development of the necessary metrology, and a wide range of measuring instruments has been devised to cater for the evaluation of surfaces and structures down to the 0.1 nm level. Particularly noteworthy are the Nanosurf, the polarizing interferometer, the stylus profilometer, the laser profilometer and the X-ray interferometer. This powerful array of instruments provides a measuring capability which ranges from 50 pm to 15 mm in surface amplitude and from 50 nm to 250 mm in surface wavelength, and techniques for roundness measurements to 1 nm and displacement calibration to 10 pm, traceable to the national standards of length.

The **specific areas** of nanotechnology/nanometrology include:

- Semiconductor and other electric surface properties in respect of charge injection/store

- Surface reagents and catalysts in respect of chemical reactions and processes
- Surfaces of biological molecules in liquids and membranes and their changes in real time
- Surfaces of magnetic heads, compact discs etc., for storage capacity
- Coatings and surfaces of tools for wear properties
- Surface effects produced by non-conventional mechanisms
- Damage monitoring of pure and hybrid materials on the atomic scale
- Tribological investigation including bearings, adhesion adsorption etc.

The **specific measurement requirements** are:

- Flow or defect detection
- Structural characterization – lattice parameters
- Position and relative position of features
- Height or topographic features
- Shapes and edge sharpness
- Volumetric analysis
- Movement of atoms
- Time changes of atomic or molecular structures

The **usual applications** go now from the basic technology to chemistry, physics and biology. The search for the spatial correlation of features as well as the appropriate identification are in general very important in dimensional metrology whereas crystalline structures or the order of molecules are typical points of interest in the field of nanotechnology.

Figure 2 shows, that great progress was achieved during the reduction of the size of the quantities to be represented. For a measuring device the capability to make possible visualisation of the surface or workpiece feature to be investigated and the quantification of this visual information are essential characteristics. In this connexion we speak about the so-called "metrological gap" [7].

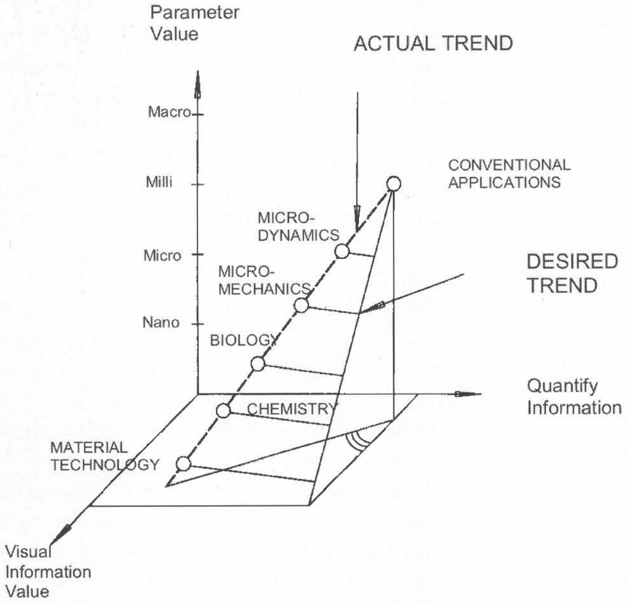


Figure 2: Metrological Gap

The reduction in the scale of features or details to be investigated has not necessarily been accompanied by an increase in the ability to quantify. Due to the inability to calibrate at the atomic level of nanotechnology there are difficulties to quantify with sufficient accuracy as is illustrated in Figure 2.

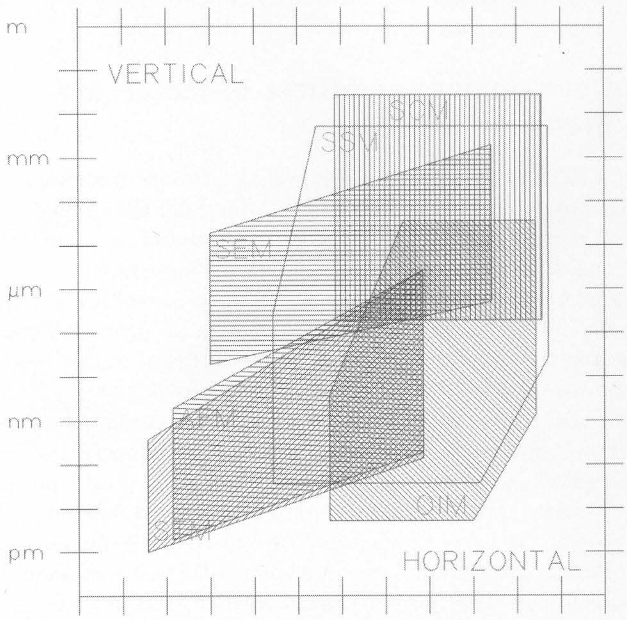
4. Instrumentation in Nanotechnology

Generally dimensional surface measurement technique has the task to recognize at explored surfaces corresponding details and magnifies greatly in most cases especially perpendicularly to the tested surface to make possible distinctions between individual lateral details. In nanotechnology and precision machining however very often smallest or even crystalline structures and molecular and atomic assignments are of special interest.

Increasingly those developments have attained since about 1980 at meaning to improve the resolution of the measurement instruments to an atomic level. This will be pursued in future still increasingly, further however also

- to reduce measurement time as well as uncertainty and
- to increase precision.

Figure 3 shows values and ranges of the measuring resolution and measuring range for the different methods used in nanometrology.



AFM	Atomic Force Microscopy
STM	Scanning Tunneling Microscopy
SEM	Scanning Electron Microscopy
OIM	Optical Interference Microscopy
SCM	Scanning Confocal Microscopy
SSM	Scanning Stylus Microscopy

Figure 3: Measuring resolution and range for different measurement methods

Extremely high accuracy demands deposit presently already at the above mentioned highly developed instruments for everyday use and high technology products in general. The fabrication of these require high precision measurements of length, voltage, frequency, velocity, pressure, radiation, temperature etc.

Laboratory research continually improves how these basic quantities are measured, a process that is inseparable from each government's constitutional responsibility for maintaining the nation's weights and measures.

In persecution of this aim since about 1982 new high resolution and high precision measuring devices have been developed [8, 9]:

- Scanning Tunnelling Microscopy (STM) and
- Atomic Force or Scanning Probe Microscopy (AFM, SPM).

For highest demands these methods make it possible to explore atomic structures and in general very accurate and small industrially produced parts and structures. Special variants of these instruments which usually involve specially prepared specimens and probes are thermal conductance, near field optical evanescence, magnetic force and electrostatic force microscopes.

5. Scanning Tunneling and Atomic Force Microscopy

Nanotechnology is an enabling technology rather than one just confined to fabrication in the nanometer region. It seems obvious that a first requirement for future instruments is that they are multipurpose and flexible. They should be fast also so that environmental effects such as thermal drift and vibration are minimized. One approach is to make an instrument which is capable of performing many different aspects of nanotechnology with the same piece of apparatus. For example, it is possible for one instrument to machine using ion beam milling, utilize the secondary electrons (SEM mode) to visualize the surface, profile the topography using an STM adaption, and possibly even to measure nano-friction and hardness. All these operations would be carried out in a continuous vacuum and would probably be able to utilize the same software and computer controller for specimen positioning.

Considering conventional optical or stylus methods and also scanning electron microscopy the typical value of the ratio of vertical resolution to lateral resolution is about 0,01. This depends typically from conventional machining with typical cutting depth to width ratio. In the field of nanotechnology at the atomic scale there are similar demands for resolution because of the need for information of the shape of small structures and the shape of for instance cells or molecules.

With scanning tunnelling and atomic force microscopes lateral resolutions better than 1 nm and in vertical direction up to 0,1 nm are achieved. So these measuring devices achieve a ratio of resolution of nearly 1 showing an important advance over the above mentioned conventional methods (Figure 4).

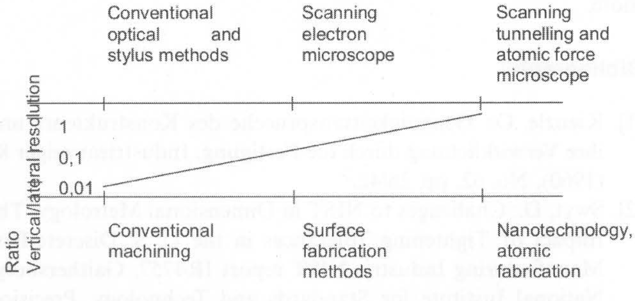


Figure 4: Development of resolution ratio

The scanning tunnelling microscope (STM) is an instrument capable of creating atomic resolution images of the surfaces of electrically conducting materials such as metals and semiconductors. The operation of that instrument is based on the so-called tunnelling current, which starts to flow in vacuum atmosphere when a very sharp tip in form of a metal needle approaches a conducting surface at a distance of approximately one nanometer or a few atomic diameters. The image comes into existence while the tip is scanned across the surface to be measured and maintained in the above mentioned distance making the tunneling current flow continuously (see Figure 5).

The tip is mounted on a piezoelectric x-y-z scanner and scanned over a specimen to reveal the contours of the surface down to the atomic level, which allows tiny movements by applying a voltage at its electrodes. Thereby, the electronics of the STM system control the tip position in such a way that the tunneling current and, hence, the tip-surface distance is kept constant, while at the same time scanning a small area of the sample surface. This movement is recorded and can be displayed as an image of the surface topography. So the image is made up of a series of line scans, each displaced in y-direction from the previous one, and displays the path the tip followed over the surface. The principle and operation of an STM are surprisingly simple. An extremely sharp conductive tip (ideally terminating in a single atom) traces the contours of a surface to be investigated with atomic resolution whereas the tip can be moved in three dimensions with an x-y-z piezo translator [9].

An STM actually traces contours of constant electron density at a particular energy determined by the bias voltage. Thus, when there are different atoms in a surface layer, atomic resolution images will depend on bias voltage. Figure 5 shows the comparison between STM and AFM.

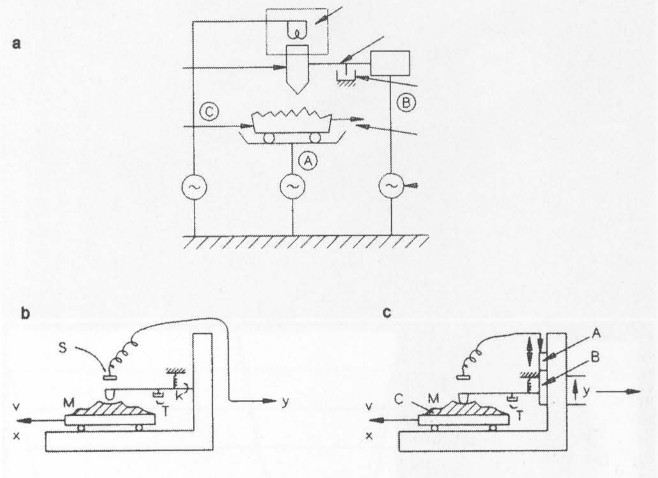


Figure 5: Schematic diagrams of STM (b) and AFM (c)

The essential features of an AFM are the tip, a spring, and some device to measure the deflection of the spring. In practice, the spring deflection sensor can be either based on electron tunneling to the back of the spring, on optical interference between the back of the spring and a reference plate, or by deflection of a laser-light beam reflected off the back of the spring.

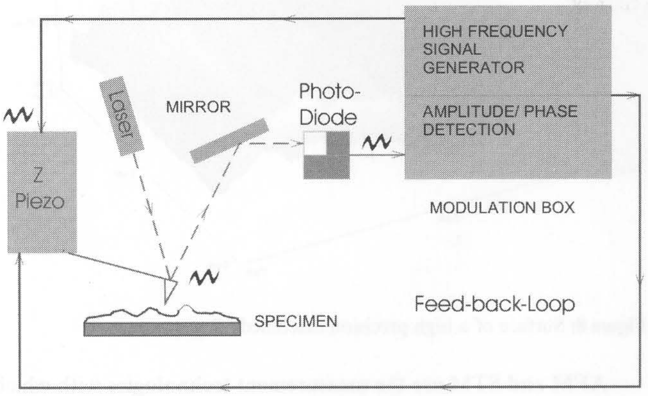


Figure 6: Basic arrangement of an AFM

In each case, the tip follows a path that is an accurate topography of the surface. No voltage is applied between the tip and the sample, and no current needs to flow between the tip and the sample. Thus the AFM can image samples with a low electrical conductivity and it is not necessary to operate in vacuum atmosphere.

The search for the spatial correlation of features as well as the appropriate identification are very important in general in dimensional metrology. Atomic structures or the order of molecules are typical points of interest in the field of nanotechnology. The structure and surface topography of precision machined parts can be investigated by that means.

Figure 7 shows a small part of the surface of a compact disc. The scanned pit length is between 0,74 µm and 5 µm. The width of the scanned pit lies between 0,35 µm and 0,81 µm. Its depth is approximately 0,1 µm. The distance between two pits has an amount of approximately 1,6 µm.

Figure 8 illustrates another practical application of atomic force microscopy. It shows the surface structure of a high precision machined alloy specimen. The length and width of the scanned area are in this case 10 µm.

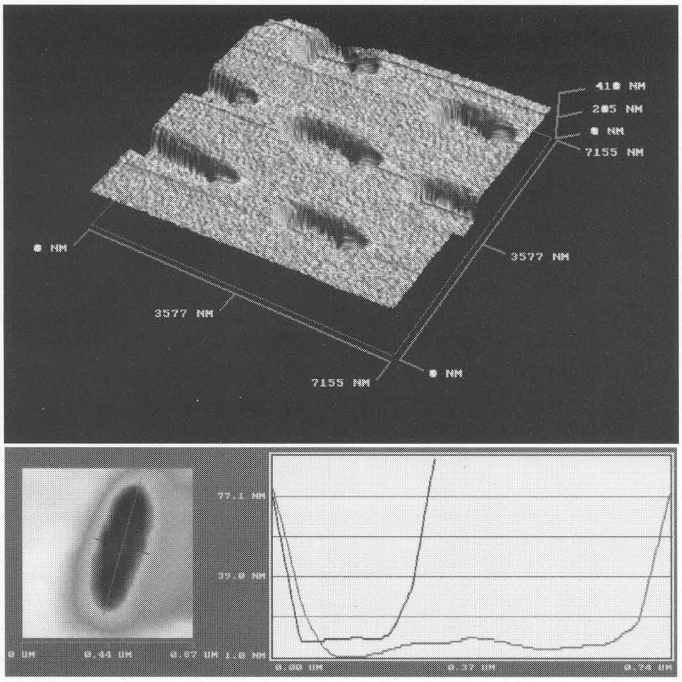


Figure 7: View of a compact disc, detail of surface and pit

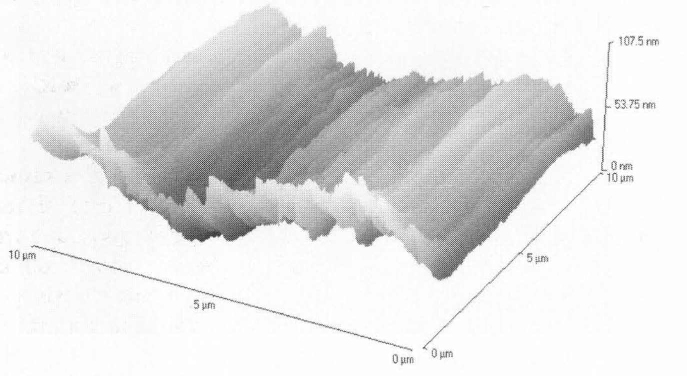


Figure 8: Surface of a high precision machined alloy specimen

AFM and STM are the measurement technologies with which it is possible to carry out measurements in micro and nano technology. Especially scanning tunneling microscopes are instruments capable of creating atomic resolution images of the surface of electrically conducting materials such as metals and semiconductors. And STM has made possible the first steps of atom manipulation which may perhaps lead in the future to fabrication at the atomic level.

6. Concluding Remarks and Outlook to Future Developments

In modern metrology it is possible to use instruments capable of creating atomic resolution images of the surfaces of different specimens. AFM and STM are such advanced measurement technologies. At the atomic level metrology and fabrication seem to be closely related. STM has made possible the first steps of atom manipulation which may perhaps lead in the future to fabrication at the atomic level.

One of the first successes experiments carried out once having learned to move atoms was to construct a row of several atoms on top of a basic surface as shown in Figure 9 [10].

As a still more futuristic development this may perhaps make possible the design and production of miniature measurement instruments or even independently working measuring robots that might perhaps operate autonomously in the micro or even nano world.

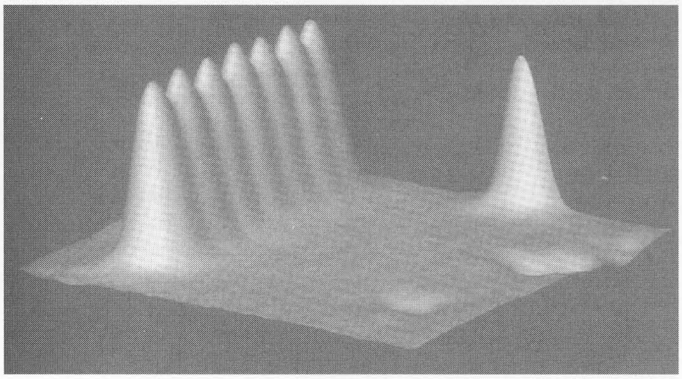


Figure 9: A row of 7 xenon atoms on top of a nickel surface constructed one-atom-at-a-time with a STM [10]

To be realistic the application of atom manipulation for technological purposes is, in the first years of the 21st century, far beyond sensible consideration. The speed and reliability that can be achieved make any idea of mass manufacturing, now, or in the foreseeable future, completely ridiculous.

But in any case nanometrology has already become technical reality and pico and femto metrology will not be impossible any more.

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Tytuł: Od nanometrologii do pikometrologii – metrologia dla ludzkiego życia i rozwoju technologicznego w XXI wieku

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Artykuł recenzowany