Standards of length at the nanoscale based on movement gages and their measurement with sub- nanometric uncertainty

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ABSTRACT

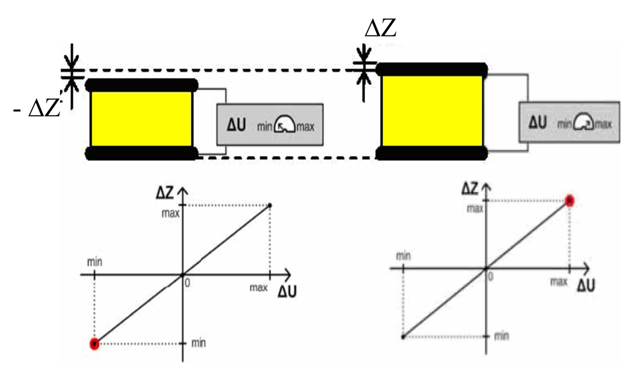
The manufacture of nano-electronic devices, nano manipulators, and microelectromechanical sensors, as well as elaborations of nano-technological processes with atomic spatial resolution have made it necessary to calibrate measuring devices at the nanoscale with sub-nanometric uncertainty [1]. The standards of length offered differ from traditional static standards in the calibrated movement of the datum surface. Essentially new types of standards are used based on movement gages. Materials with a reverse piezoelectric effect which differ from piezoelectric ceramics in their multifold smaller hysteresis, creep, and nonlinearity are used in the new standards for horizontal or vertical movement. The amount of movement of the gage surface is directly proportional to the amount of applied voltage. The range of movement of these gages amounts to more than 100 nanometers vertically and more than 200 nanometers horizontally.

Keywords: standards, nanometer, subnanometer, movement.

The manufacture of nano-electronic devices, nano manipulators, and microelectromechanical sensors, have made it necessary to calibrate measuring devices at the nanoscale with sub-nanometric error. Traditional standards of length at the nanoscale are manufactured as depressions of different configurations on the surface. As the size of the standards and the coefficient of their technological error decrease, their relative manufacturing error only increases. The increase in relative manufacturing error is only one of the reasons why there are no 1-nanometer, 10-nanometer, etc. standards at the nanoscale or will be any time soon. Other important reasons for not using traditional standards of the nanoscale are as follows:

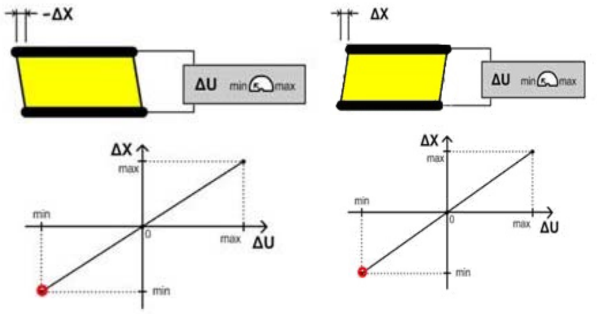
1. the surface becomes almost instantly covered with an adsorbed layer of molecules from the atmosphere;
2. physical-chemical reactions occur on the surface (oxidation, migration, diffusion, etc.);
3. dust contamination not only with nano, but also with micro particles, the dimensions of which amount to hundreds and thousands of nanometers.
4. absence of probes on the market with categorized tip profiles

The traditional way to overcome these problems is to wait for nanotechnology to develop to nano- and sub-nanometric resolution ability, while working with expensive vacuum measuring devices and in cleanrooms is also holding up the use of nanotechnology. The NANOmeter Standard Company has solved these problems in a different way. Instead of immobile static standards, it has manufactured standards with a controlled moveable surface. Movement of the surface of these standards is ensured by placing the upper surface on material which has an inverse piezoelectric effect. Materials with different polarities are used for vertical and horizontal movement (Fig.1,2). It should be noted that materials with multifold smaller hysteresis, nonlinearity, and creep are used for decreasing the shortcomings of ordinary piezoelectric ceramics.



The surface position - ΔZ of the standard after applying voltage of negative polarity -ΔU	The surface position + ΔZ of the standard after applying voltage of positive polarity +ΔU

Figure 1: The new standard's movement in Z direction.



The surface position - ΔX of the standard after applying voltage of negative polarity - ΔU

The surface position + ΔX of the standard after applying voltage of positive polarity + ΔU

Figure 2: The new standard's movement in X direction.

The dependence of the amount of movement on the control voltage measured with subnanometer uncertainty in an optical interferometer shows on Fig.3.

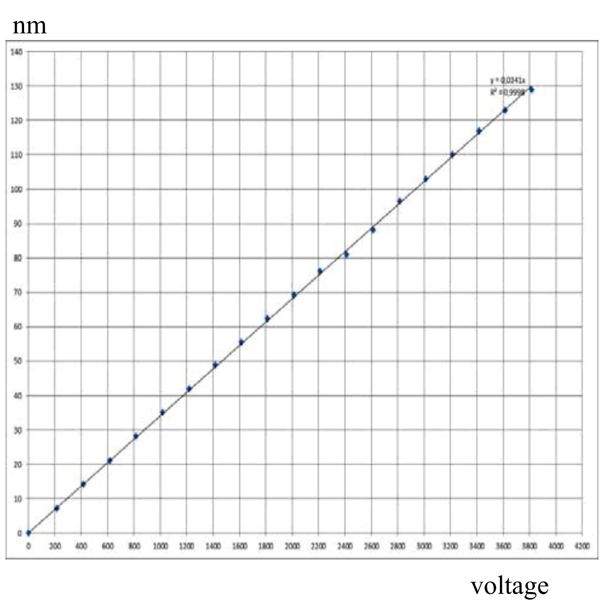


Figure 3: Dependence of vertical displacements from amplitude of voltage impulses.

In horizontal movement standards, the upper surface moves in one direction when the control voltage of one polarity is applied to the piezoelectric material, while surface movement changes in the opposite direction when the polarity of the control voltage changes. Similar processes also occur when using vertical movement standards. Horizontal movement of the standard surface in real time can be seen using an electronic microscope, as shown on Fig.4.

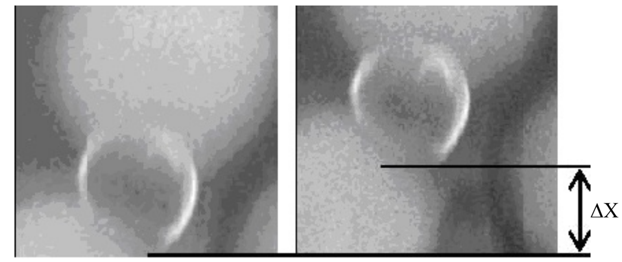


Figure 4: Surface scanning in electron microscope before and after horizontal displacements.

Similar measurements of the movement of the standard surface are produced in scanning probes (atomic force or tunnel) microscopes.

In order to carry out vertical calibration, a vertical movement standard is placed on the microscope stage. Then a probe is brought to the surface and held at a fixed distance with the help of a tracking device. It should be noted that the error of holding the probe relative to the surface amounts to a hundredth fraction of a nanometer. When moving the datum surface of the standard vertically, the tracking device of the microscope moves the probe in the same direction and at the same distance (with a precision determined by the error of the tracking device). The probe is moved by moving the manipulator and is equal to the amount of calibrated movement of the datum surface of the standard. Calibration of the measuring device vertically is done by defining different movements of the standard surface and measuring them. The same thing is done when carrying out calibration horizontally

The standards of length offered differ from traditional static standards in the calibrated movement of the datum surface. Essentially new types of standards are used based on movement standards. The amount of movement of the standard surface is directly proportional to the amount of voltage applied. The range of movement of these standards amounts to more than 100 nanometers vertically and more than 200 nanometers horizontally.

Signals controlling the movement of the datum surface of the standards are generated by an electronic control unit. The amount of movement of the datum surface of the standards does not depend on factors that distort the configuration of the surface of traditional static standards, but is determined only by the electromechanical characteristics of the entire volume of the piezoelectric material.

The long-term stability of the material used ensures many years of service of the movement standard even when used outside cleanrooms and vacuum sources. Movement of the surface occurs in the fraction of a second, which makes it possible to:

- ensure high reproducibility of the results of surface movement, since the characteristics of the datum surface do not change in this time even when used in an ordinary atmosphere;

- reduce the time of calibration of the measuring equipment.

The amount of movement of the datum surface corresponding to the amount of measurement relayed to the device does not depend on the configuration of the datum surface or, consequently, on the level of development of nanotechnology. What is more, the amount of movement does not depend on the configuration and slow, compared to the movement time, changes of the surface.

Let us compare the technical specifications of the equipment when carrying out calibration using traditional static standards and movement standards.

The following is required when using static standards:

1. The surface of the standards must be clean. This is hard to accomplish, since it is not easy to clean the already contaminated surface without changing its configuration.

2. Measurement results of the probe profile tip. Such measurements can potentially be carried out, if there is a clean standard surface with known profile and a calibrated manipulator, but this specification is difficult to perform owing to the technical problems entailed in manufacturing and preserving such a surface. Moreover, the specification that a calibrated manipulator be available until the end of the calibration procedure cannot be performed because the device has not yet been calibrated.

3. The probe profile must remain constant during calibration, even in the vertical direction, but it can change owing to the adsorption of particles and the emergence of mechanical defects.

When calibrating a measuring device using movement standards, it is not necessary to execute the abovementioned specifications, including those that are impossible to perform in reality or which are essentially contradictory. So error decreases multifold, reproducibility increases, and measurement time is reduced.

Movement was measured using Michelson interferometers (Fig5.a, b). Lasers with a continuous performance time of more than 10 years were used in the interferometers. Pump energy stabilization systems and temperature stabilization of resonance frequency of the external optical resonator were used to ensure relative stability of radiation frequency with a precision of up to 10^{-4}-10^{-5}. Several additional devices were used to stabilize the laser radiation frequency to 10^{-6} and less—from heat-stabilized resonators to cesium cells with a thin absorption line and electronic control systems ensuring adjustment of radiation frequency to the absorption peak. The hum level of the interferometers amounted to 0.1-0.3 nm.

a)

b)

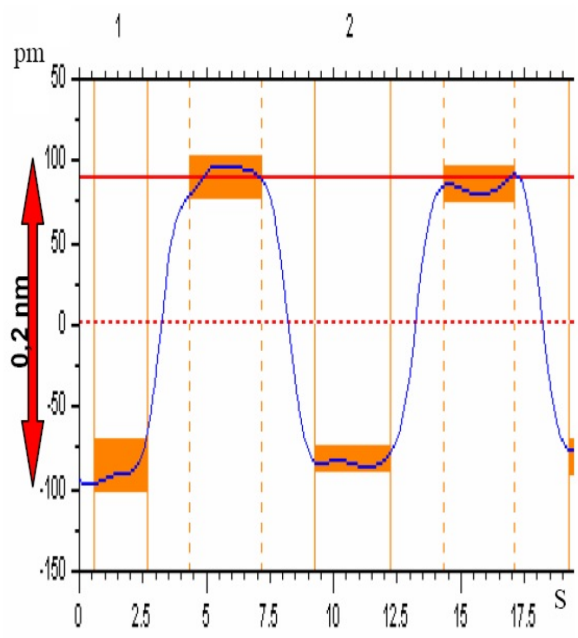
Figure 5: Different types of interferometers

a) Stabilization frequency by temperature and current.
b) Stabilization frequency by temperature, current and cezium cell.

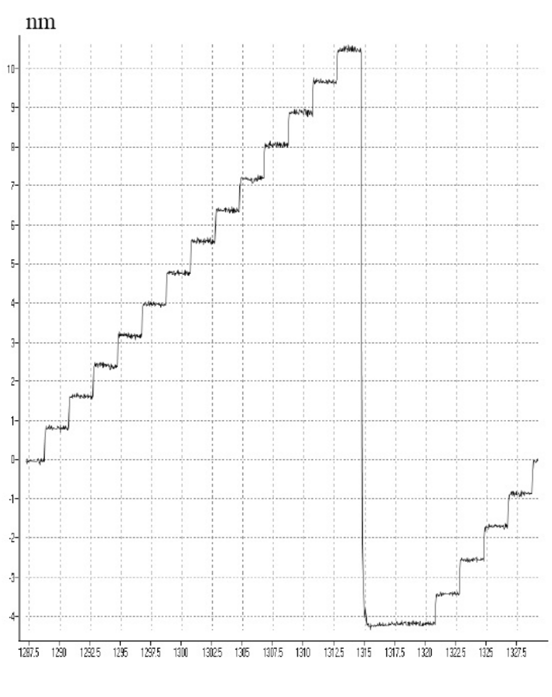
Optical interferometers come in different designs: from stationary devices, to which the object whose movement is being measured can be docked, to compact units installed in scanning probe microscopes, linear manipulators, movement sensors, and so on.

The compactness of movement standards makes it possible to use them for calibration at the nanoscale with sub-nanometric uncertainty of atomic force and other scanning probe microscopes, electronic raster and transmission microscopes, optical interference microscopes, and sensors based on microelectromechanical systems.

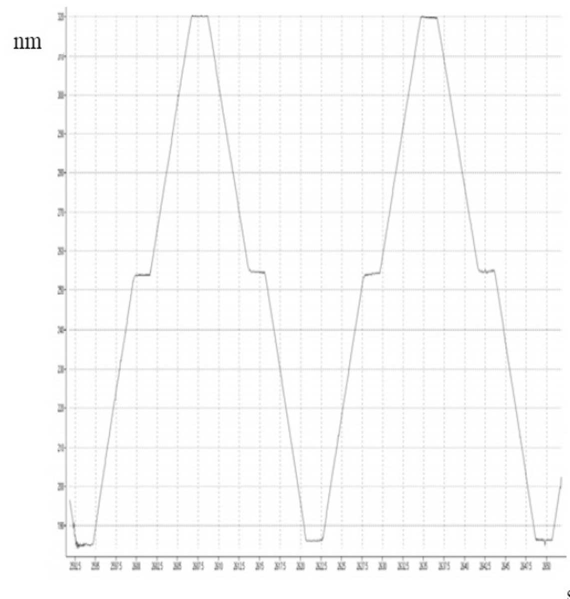
Fig.6 a,b,c presents the results of differing measuring calibrated graphs of vertical movement standards.



a)



b)



c)

Figure 6; a,b,c: The results of measuring of vertical movement of standardsб controlled by electronic control system.

Graph confirms the possibility of replacing many static standards with one standard, as well as the standard’s efficiency throughout the nanoscale and even at the sub-nanoscale.

REFERENCES

[1] Gunter Wilkening, Ludger Koenders, Gunter Wilkening, "Nanoscale Calibration Standards and Methods: Dimensional and Related Measurements in the Micro- and Nanometer Range", 1997-2012, www.barnesandnoble.com.