Bimorph cylindrical piezoceramic scanner for scanning probe nanomicroscopes

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Abstract

The article is devoted to the problems of piezoscanners. The analysis of existent domestic and foreign constructions of piezoscanners is carried out. It is certain that existent constructions have a lot of shortcomings, basic from which – an insufficient range of scanning. A novel construction of the piezoscanner is developed on the basis of a bimorph cylindrical element. The standard of developed piezoscanner is made and the results of experimental researches, in which the mutual influence between actuators on XYZ the co-ordinates is reduced.

Keywords: nanotechnology, scanning probe microscopy, piezoceramic scanner

Introduction

Nanotechnology possesses an ability to manipulate separate atoms and molecules for creation of nanostructured materials and nanoobjects, what creates a real interest for technological applications [1, 2].

Progress in nanotechnology is stimulated by development of experimental methods, most informative of which is scanning probe microscopy. The world is obliged to the invention of the scanning probe microscopy to the Nobel prize winners of 1986 - to H. Rohrer and G. Binnig [1, 2, 3].

The scanning probe microscopy (SPM) is one of the powerful modern research techniques that allows to investigate the morphology and the local properties of a solid body surface with a high spatial resolution. Currently, practically even research in the field of surface physics and thin-film technologies applies the SPM techniques [1, 2].

The analysis of a surface micro relief and of its local properties is performed by scanning probe microscopes using specially prepared tips in the form of needles. The size of the working part of such tips (the apex) is about ten nanometers. The usual tip – surface distance in probe microscopes is about 0.1-10 nanometers [2].

Various types of interaction of the tip with the surface are exploited in different types of probe microscopes. For example, the tunnel microscope is based on the phenomenon of a tunneling current between a metal needle and a conducting sample; various type of interactive force underlie the working mechanism of atomic force, magnetic force and electric force microscopes.

To keep constant the value of some parameter P characterizing the interaction of a tip with a surface, (equal to the value P_0, set by the operator) a feedback system (FS) is used. If the tip-sample distance changes, there is a change in the parameter P. In the feedback system a differential signal ($\Delta P = P - P_0$) is amplified and fed to the piezoelectric transducer that controls the tip-sample separation. The scanner uses the signal ΔP to change the separation, bringing it back to the initial value, corresponding to a differential signal close to zero. Thus it is possible to control the tip-sample distance with a high accuracy.

A block-diagram of the feedback system in scanning probe microscope is shown on Fig. 1.

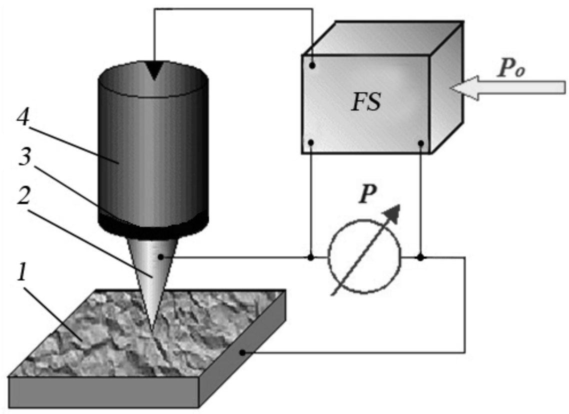

Fig.1. **Block-diagram of the feedback system of scanning probe microscope: FS – feedback system; *P* – measurable parameter; P_0 – set parameter; 1 – investigated surface (sample); 2 – probe (tip); 3 – probe holder; 4 – piezoceramic scanner**

In existing probe microscopes the accuracy in the tip-surface distance control reaches the value of ~0.01 angstrom. During tip movement along the sample surface the sample topography induces changes in the interaction parameter P. The feedback system restores the present value of the tip-sample distance in a real time.

Scanner is the basic element in a scanning probe microscopy. Scanners are made of piezoelectric materials, which on hand, provide high inflexibility of construction, and on the other hand provides possibility produce very small displacement, up to picometers.

Practically in all scanning probe microscopes the piezoelectric scanner is utilized as a very thin positioning device which moves a probe with respect to a sample or the sample with respect to a probe. The scanner is provided by two independent motions of the probe: scanning along the surface of sample (in the XY plane) and moving in direction perpendicular to the surface (the Z axis).

Problem and approach

Tubular piezoelements are widely used in the scanning probe microscopy. Tubular piezoelements are hollow thin-walled cylinders with electrodes (thin metal layers), plated on the external and internal tube surface, the end tube faces remain uncoated [2].

The scanners made of the one tubular element are most widely used in the scanning probe microscopy [2]. The structure of a tubular scanner and the arrangement of electrodes are presented in Fig. 2. The polarization vector is directed radially. The internal electrode is usually continuous. The external electrode is divided by cylinder generatrixes into four sections. When differential-mode voltage is applied to the opposite section of the external electrode (with respect to the internal electrode) part of the tube reduces in length (where the field direction coincides with the polarization direction), and increases (where the field and polarization directions are opposite). This leads to a bend of the tube and produces scanning in the X, Y plane. Change of the internal electrode potential with respect to all external sections results in lengthening or reduction of the tube along Z axis. Thus, it is possible to implement the tree-coordinate scanner on the basis of one piezo-tube. Real scanning elements frequently have a more complex structure; however the working principle remains the same [2, 3].

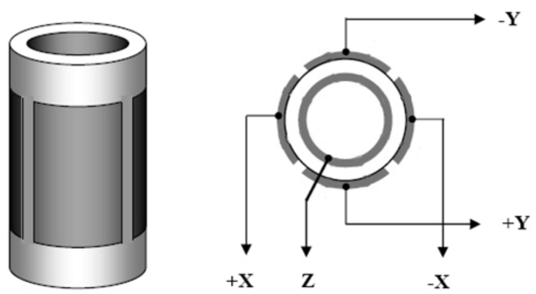

Fig.2. **Scanner made of a single tubular piezoelement**

Principal drawback of piezoceramic scanners is that at scanning in one direction of a piezotube deformed in a perpendicular direction, there is a strong interaction between the actuators responsible for moving in XYZ axes, what worsens accuracy of positioning (Fig. 3).

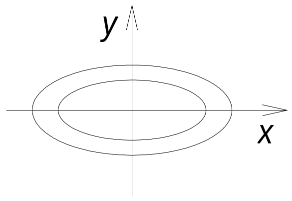

Fig.3. **Mutual influence of actuators on movement of XY axis**

The plane of the probe holder (object) is changed by the angle of slope at scanning, what narrows a scanning range. Because the actuators of the tubular scanner are rigidly coupled between their self, not taking part in moving actuators hinder a bend and that narrows the scanning range also. In addition, one of negative factors is a high control voltage up to 300V.

For elimination of drawbacks indicated above it was suggested to decrease the mutual influence between the actuators on XYZ axes [4]. Reduction of cross-coupling became possible due to the division of the scanner actuators on XY axes. For this purpose cuts are done along the piezotube, as a result four independent actuators appeared, which in pairs provide movement on XY axes, that allowed to position the scanner more precisely. In addition the actuators part on XY axes is separated from the actuator on Z axis, which became possible due to introduction of flat resilient elements (plates) having different inflexibility on XY axes, what allowed to move the holder of the object in one plane. In addition, actuators are made as bimorphs piezoelements, that causes the substantial change of descriptions of piezoscanner - the scanning range and mechanical durability are considerably increased (Fig. 4) [5]. As a holder of the probe (sample) the bimorph piezoelement is also utilized.

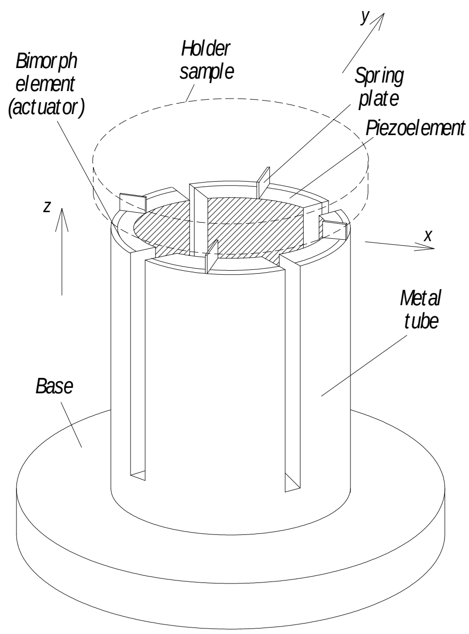

Fig.4. **Piezoceramic scanner based on bimorph tube**

Displacement of the butt end of the bimorph of piezoelectric tube on axes X, Y can be found from empiric formula [6]:

$$\Delta_{x,y} \approx \frac{2\sqrt{2d_{31}UL^2}}{\pi Dh} \qquad (1)$$

were U is the voltage which is applied on the segments of the piezoelectric tube, d_{31} – piezoelectric constant, L – height of the piezoelectric tube, D – diameter of the piezoelectric tube, h – wall thickness of the piezoelectric tube.

Vibrations of the radially polarized piezoceramic cylinder, excited by external harmonic voltage, in accordance with the character of loading, is given by the system of equations (as independent functions variables $u_2, \sigma_{rr}, \sigma_{rz}, u_r, \varphi, D_r$ are chosen) [7]:

$$\frac{\partial u_z}{\partial r} = -\frac{\partial u_r}{\partial z} + \frac{1}{c_{55}^E}\left(\sigma_{rz} - e_{15}\frac{\partial \varphi}{\partial z}\right),$$

$$\frac{\partial \sigma_{rr}}{\partial r} = \frac{1}{r}\left(c_{12}^E + \frac{\Delta_2}{\Delta_1}\right)\frac{\partial u_z}{\partial z} - \frac{1}{r}\left(1 - \frac{\Delta_4}{\Delta_1}\right)\sigma_{rr} -$$

$$-\frac{\partial \sigma_{rz}}{\partial z} - \left[\rho w^2 - \frac{1}{r^2}\left(c_{11}^E + \frac{\Delta_2}{\Delta_1}\right)\right]u_r + \frac{1}{r}\frac{\Delta_3}{\Delta_1}D_r,$$

$$\frac{\partial u_z}{\partial r} = \frac{1}{\Delta_1}\left(\Delta_4\frac{\partial u_z}{\partial z} + \varepsilon_{33}^S\sigma_{rr} - \frac{1}{r}\Delta_4 u_r + e_{33}D_r\right),$$

$$\frac{\partial \sigma_{rz}}{\partial r} = -\rho w^2 u_z - \left(c_{11}^E + \frac{\Delta_2}{\Delta_1}\right)\frac{\partial^2 u_z}{\partial z^2} - \frac{\Delta_4}{\Delta_1}\frac{\partial \sigma_{rr}}{\partial z} -$$

$$-\frac{1}{r}\sigma_{rz} - \frac{1}{r}\left(c_{12}^E + \frac{\Delta_2}{\Delta_1}\right)\frac{\partial u_r}{\partial z} - \frac{\Delta_3}{\Delta_1}\frac{\partial D_r}{\partial z},$$

$$\frac{\partial \varphi}{\partial r} = \frac{1}{\Delta_1}\left(-\Delta_3\frac{\partial u_z}{\partial z} + \varepsilon_{33}\sigma_{rr} - \frac{1}{r}\Delta_3 u_r + c_{33}^E D_r\right),$$

$$\frac{\partial D_r}{\partial r} = \frac{1}{c_{55}^E}\left(-e_{31}\frac{\partial \sigma_{rz}}{\partial z} + \Delta_5\frac{\partial^2 \varphi}{\partial z^2}\right) - \frac{1}{r}D_r. \qquad (2)$$

were $\Delta_1 = e_{33}^2 + c_{33}^E\varepsilon_{33}^S$;

$\Delta_2 = c_{33}^E e_{31}^2 - 2c_{13}^E e_{31}e_{33} - c_{31}^2\varepsilon_{33}^S$;

$\Delta_3 = c_{13}^E e^{33} - c_{33}^E e_{31}$;

$\Delta_4 = c_{13}^E\varepsilon_{33}^S + e_{31}c_{33}$;

$\Delta_5 = e_{15}^2 + c_{15}^2\varepsilon_{11}^S$,

ε_{31}^S is the tensor of deformation;

ρ is the density;

r is the middle radius of cylinder;

c_{33}^E is the tensor of the module of elasticity;

e_{31} is the piezoelectric constant.

It is possible to show after transformations, that the solution of the task about the forced vibrations of the radially polarized cylinder at the electric loading is taken to the solution of the infinite sequence of the systems of usual differential equations [7]:

$$\frac{du_z^{(n)}}{dr} = -\eta_n u_r^{(n)} + \frac{1}{c_{55}^E}\left(\sigma_{rz}^{(n)} - \eta_n e_{15}\varphi^{(n)}\right),$$

$$\frac{d\sigma_{rr}^{(n)}}{dr} = \frac{1}{r}\eta_n\left(c_{12}^E + \frac{\Delta_2}{\Delta_1}\right)u_z^{(n)} - \frac{1}{r}\left(1 + \frac{\Delta_4}{\Delta_1}\right)\sigma_{rr}^n +$$

$$+\eta_n\sigma_{rz}^{(n)} - \left[\rho w^2 - \frac{1}{r}\left(c_{11}^E + \frac{\Delta_2}{\Delta_1}\right)\right]u_r^{(n)} + \frac{1}{r}\frac{\Delta_3}{\Delta_1}D_r^{(n)},$$

$$\frac{d\sigma_{rz}^{(n)}}{dr} = \left[-\rho w^2 - \eta_n^2\left(c_{11}^E + \frac{\Delta_2}{\Delta_1}\right)\right]u_z^{(n)} - \eta_n\frac{\Delta_4}{\Delta_1}\sigma_{rr}^{(n)} - \qquad (3)$$

$$-\frac{1}{r}\sigma_{rz}^{(n)} - \frac{\eta_r}{r}\left(c_{11}^E + \frac{\Delta_2}{\Delta_1}\right)u_r^{(n)} + \eta_n\frac{\Delta_3}{\Delta_1}D_r^{(n)},$$

$$\frac{du_r^{(n)}}{dr} = \frac{1}{\Delta_1}\left(\eta_n\Delta_4 u_z^{(n)} + \varepsilon_{33}^S\sigma_{rr}^{(n)} - \frac{\Delta_4}{r}u_r^{(n)} + e_{33}D_r^{(n)}\right),$$

$$\frac{d\varphi^{(n)}}{dr} = \frac{1}{\Delta_1}\left(\eta_n\Delta_3 u_z^{(n)} + \varepsilon_{33}^S\sigma_{rr}^{(n)} - \frac{\Delta_3}{r}u_r^{(n)} + c_{33}^E D_r^{(n)}\right),$$

$$\frac{dD_r^{(n)}}{dr} = \frac{\eta_r}{c_{55}^E}\left(e_{15}\sigma_{rz}^{(n)} - \eta_n^2\Delta_5\varphi^{(n)}\right) - \frac{1}{r}D_r^{(n)}.$$

With regional terms

$$\varphi(n)\Big|_{r_{0\pm h}} = \pm\frac{2V_0}{n\pi}\left[\sigma_{rr}^{(n)}(r) = \sigma_{rz}^{(n)}(r)\right]_{r_{0\pm h}} = 0$$

were $\eta = n\pi / l$;

n is the number of the harmonic;

l is the length of the piezoceramic cylinder;

V_0 is the amplitude of the exciting vibrations.

The solution of these equations presents considerable difficulties, therefore we shall define basic descriptions of a bimorph piezoceramic cylinder experimentally.

Cylindrical bimorph piezoceramics elements until now have not been studied. If the radius of the cylindrical bimorph piezoelement, approaches infinity, it is possible to talk about flat bimorphs piezoelements.

Displacement of the free end of the cantilever-fastened bimorph piezoelement, and correspondingly, the scanning range, is possible to calculate by [5, 8]:

$$\xi \approx \frac{3}{2}\cdot\frac{d_{31}\left[\left(h_p + \frac{h_M^2}{2}\right) - \frac{h_M^2}{4}\right]\cdot\left(1 + 2\cdot\frac{L-1}{l_p}\right)\cdot l}{\left[E_M\cdot S_{11}^E\cdot\frac{h_M^3}{8} + \left(h_p + \frac{h_M}{2}\right)^3 - \frac{h_M^3}{8}\right]\cdot h_p}\cdot U$$

were E_M is the Young's modulus of metal plate;

d_{31} is the piezoelectric modulus;

S_{11}^E is the elastic constant;

h_M is the thickness of metal plate;

h_P is the thickness of piezoelement;

l is the length of piezoelement;

L is the length of metal plate;

U is the control voltage.

In the experiment a cylinder was utilized made of the ceramics of PZT-19 [4] with the external diameter 30 mm, the internal diameter 25 mm, the height of the cylinder 16 mm (see Fig. 4, 5).

Piezoscanner works as follows. When of the meander voltage on two diametrically opposite bimorphs elements is applied there is the synphased movement of these elements which are utilized for scanning in axes X and Y.

For this scanner the coefficients of connection are certain between actuators on XYZ axes. Determination of this coupling is needed, because they define the undesirable movement of the probe in other axes. Research was carried out as follows. On one of the actuators the voltage was applied of the resonance frequency which corresponds to the bending vibration of the scanner, and from other actuators the voltage was picked up at the same frequency. As experiments showed at the resonance frequency (7 kHz) of one actuator the oscillation of other actuators are lower eight times, e.g. does not exceed -18,3 dB, what means that the vibrations of one actuator do not render substantial influence on other actuators of the scanner.

In addition, the obtained results showed that the amplitude of vibrations of the piezoscanner in X and Y axes was increased approximately 1.7 times.

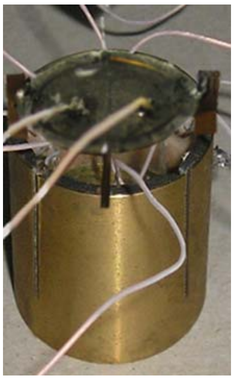

Fig.5. **Experimental sample of bimorph of the tubular piezoceramic scanner**

Conclusions

The developed and tested experimental sample of a piezoelectric scanner on the basis of bimorph cylindrical element in which the cross-coupling is reduced between actuators on XYZ axes. It became possible due to the separation of actuators from each other, and also to introduction of flat resilient plates, having different inflexibility in perpendicular directions. In addition, the developed scanner allows to increase a scanning range.

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Bimorfiniai cilindriniai pjezoelektriniai keraminiai nanomikroskopų skenavimo zondams skirti skeneriai

Reziumė

Aptartas poreikis spręsti aktualias pjezoelektrinių skenerių problemas. Žinomų šalies ir užsienio skenerių trūkumai – nepakankama skenavimo zona. Naujojoje pjezoelektrinio skenerio konstrukcijoje yra panaudotas cilindrinis bimorfinis elementas. Toks pjezoelektrinis skeneris jau pagamintas ir atlikti eksperimentiniai jo tyrimai.

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