Investigation of the influence of the geometric parameters of AFM cantilevers on the resonant frequency of their oscillations

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Abstract. This paper presents the results of theoretical and experimental studies aimed at studying the influence of the basic geometric parameters of micromechanical cantilevers on the resonant frequency of their oscillations. The dependences of the oscillation frequency on the length of the cantilever beam, obtained based on mathematical modeling are theoretically investigated by the finite element method. In experimental studies that used AFM cantilever beams, the beams were shortened stepwise by the method of local ion beam etching by focused ion beam (FIB) Ga⁺. After each step, the change in the resonant frequency of oscillations was monitored. It was found that the application of the FIB method allows you to accurately change the geometric parameters of the probe beams, which, in turn, allows you to change the resonant frequency of cantilever oscillations with high accuracy. During the analysis of the obtained dependences of the resonant frequency of oscillations on the geometric parameters of the beams, it was found that a decrease in the length of the cantilever from 110 to 80 μm leads to an approximately twofold increase in the resonant frequency of oscillations of the cantilever from 320 to 620 kHz. The obtained graphs of the theoretical and experimental dependencies are compared, which showed a good correlation of the results.

1. Introduction
Micromechanical structures are widely used in the creation of sensors for various purposes. Cantilever beams coated with a layer of a sensitive substance are widely used in the creation of liquid and gas sensors for medicine, environmental monitoring and technosphere safety systems. When this is detected, usually by optical methods, either the bend of the beam, or a change in the frequency of its vibrations. Therefore, to ensure maximum detection efficiency, it is necessary to ensure optimal values of the resonant frequencies of the beams, usually around 500 kHz. In addition, cantilever beams oscillating at resonant frequencies with tips at the end are used as cantilever sensors in scanning probe microscopy. Scanning probe microscopy (SPM) is by far one of the most common and promising methods for studying the surface with subnanometer resolution. Various AFM techniques provide information on the surface topography, its mechanical and electrical parameters. This technology not only allows obtaining surface images with atomic resolution, but also provides a wide range of possible applications in the manufacture of nanoelectronic elements.
It is very important to consider the value of the resonant frequency of the cantilever beam of the chip in SPM. A compromise between the maximum field of view and the resonant frequency of the probe microscope is a necessary measure when using modern SPM designs. The use of probes with a rigid structure allows the use of a high resonant frequency, tracking signals in a wide frequency band with enough accuracy and reducing the effect of external noise on the scan results. High resonant frequency makes it possible to provide research at higher scanning speeds, which reduces the time taken to obtain the necessary information about the surface. Also, a decrease in the scanning time entails a decrease in the influence of temperature drift, which favorably affects the quality of the obtained image [1].

The resonant frequency of the cantilever largely depends on such terms as the material of the probe sensor and the geometric parameters of the beam itself. By changing the shape of the probe beam, you can change its resonant frequency in a wide range. Changing the geometric parameters of the probe beams with high accuracy and speed can be performed using local ion-beam etching using the FIB method.

The FIB method allows in high vacuum conditions to perform technological operations of local ion beam milling and ion-induced deposition of materials from the gas phase without the need for resistors, masks and chemical etchants [2-5]. A wide range of materials deposited by this method allows the use of FIB in the formation of nanoscale structures, in particular, probes for nanodiagnostics.

The aim of this work is to establish the dependence of the resonant frequency of oscillations of the AFM probe cantilever on its geometric parameters.

2. Theory
A theoretical study of the dependence of the resonant frequency on the geometric parameters of the cantilever was carried out in the approximation of a simple rectangular beam, for which the relationship of the resonant frequency with the dimensions of the cantilever and the beam material in vacuum is described by equation (1).

\[ \omega_{beam} = \frac{t}{2\pi l^2} \sqrt{\frac{E}{p_c}} \]

where \( t \) is the thickness of cantilever, \( l \) is the length, \( E \) is the elastic modulus of the cantilever material, and \( p_c \) is the density of the cantilever material. Obviously, with a decrease in the length of the beam by a factor of 2, the resonant frequency will increase by 4 times, and there is a direct dependence on the thickness of the beam, but its change affects the resonant frequency much weaker than the length. Based on this, in the present work, it was precisely the dependence of the resonant frequency of oscillations on the length of the cantilever beam that was studied.

Traditionally, when forming chips for SPM, poly-Si is used as the cantilever material, since it is optimal from the point of view of mechanical properties. During the theoretical and experimental studies, poly-Si was used in the work to coordinate cantilevers with traditional technological processes and to reduce calculation errors.

In the work, both theoretical and experimental studies are carried out for beams for which there is no probe at the end of the cantilever. This is necessary to determine the true dependence of the resonance frequency on the length of the beam without inert mass, which can distort the simulation results and introduce an additional error. If necessary, the tip can be grown by local ion-induced FIB deposition.

We obtained the dependence of the resonance frequency on the beam length shown in Figure 1 (a), based on equation (1).
3. Modelling

Modeling the cantilever beam by the finite element method allows one to obtain results that are closest to reality due to the possibility of constructing the exact geometry of the probe sensor and much more complex mechanisms and algorithms used in the calculation, allowing to obtain resonant frequencies for the constructed model. The model was built and shown in Figure 2, based on the available data.

Figure 1. Theoretical dependence of the resonant frequency on the beam length in the range (a) from 10 $\mu$m to 110 $\mu$m and (b) from 40 $\mu$m to 110 $\mu$m

The obtained dependence has an exponential character, which is explained by the beam oscillation mechanism. The use of very short beams is impractical, since the error in the length of the beam increases, and the effective length for using probes also decreases. Due to these reasons, as well as to comply with experimental studies, the length range has been reduced.

Figure 1 (b) shows that the exponential nature of the graph in this range is not so pronounced, which is a favorable factor, since in practice this will allow achieving approximately the same resonant frequency on several probes and reducing the error in constructing the experimental dependence.

Thus, it is noted that the obtained dependence fully reflects the physics of the processes occurring during cantilever oscillations and confirms the validity and possibility of using formula (1) in the description of such systems.
The results of a series of studies allowed us to construct a graph reflecting the dependence of the resonant frequency on the length of the beam, which is shown in Figure 3.

![Graph showing the dependence of the resonant frequency on the beam length](image)

**Figure 3.** The dependence of the resonant frequency on the beam length in the range from 40 µm to 110 µm, built based on modeling

It can be seen from the graph that the curve describes an exponential dependence like that obtained during analytical modeling. The discrepancies in the values of the resonant frequencies are explained by the fact that when modeling by the finite element method, much more various parameters of both the probe sensor itself and the research method are taken into account, for example, the beam width or the mesh used in the simulation and its quality in narrow sections. A slight kink in the lower part of the graph is explained by the fact that at the given lengths of the beam there is an oscillation of the chip itself, the peak of influence of which falls on 90 µm. The rest of the graph in Figure 3 confirms the data obtained in the calculations using analytical expressions.

4. Experimental

Experimental studies were carried out using a Nova NanoLab 600 electron microscope equipped with a FIB system [2]. Three NSG10 probe sensors were used as samples, the tips of which were broken during intensive use. The beam material is poly-Si. The remainder of the initial probe can introduce distortions into the result, since it is an inert mass, therefore, at the first stage of the study, using the FIB ion-beam etching, the remaining tip elements of each cantilever were removed. Figure 4 shows the probe beam before and after FIB milling.

![Probe beam images](image)

**Figure 4.** Cantilever of probe (a) before milling and (b) after milling
The resonance frequencies of the beams prepared for the study were measured using the scanning probe microscope Solver P-47 PRO. Since the probe sensors used in the work have two beams, one on each side, with the initial lengths of 123 μm and 93 μm, the experimental results will be divided into 2 groups - graphs for initially long beams and graphs for initially short. At the next stage, all the beams were alternately shortened with a step of 10 μm, and their resonance frequencies were fixed. From the obtained statistics, the dependencies shown in Figure 5 were built.

![Graphs](image)

**Figure 5.** Experimental dependence of the resonant frequency on the beam length (a) for 123 μm beams and (b) for 93 μm beams

Our studies have shown that the cantilevers have a different thickness from 2.5 to 3 mkm. As a result, the curves obtained in Figure 5 are not a continuation of each other and cannot be combined into one graph, due to the strong difference in resonant frequencies at a point with a long beam of 80 μm Figure 5 (a) and at a point of 70 μm Figure 5 (b).

The discrepancy between the curves on the graph for beams with an initial length of 93 μm is most likely due to the fact that since the length of the beam is small, any errors during etching or measuring the length of the cantilever have a much stronger effect on the final result of measuring the resonance frequency, due to the exponential dependence a wider range, as in Figure 1 (a). That is, for beams having a length of less than 50 μm, a change in one of the basic parameters of the probe sensor, for example, the length of the beam, has a greater effect on the resonant frequency than for longer cantilevers.

Differences in resonant frequencies for one beam length, for example, for a point of 100 μm (Figure 5 (a)), are associated with the presence of a large number of resonant frequencies for longer cantilevers, the value of which is automatically determined by the measuring system.

Thus, for various cantilever beams, dependences are obtained that allow predicting the value of the resonance frequency for a certain cantilever length and, in general, the dependence trends coincide for all 3 experimental samples. Also, the experimental data correlate well with the theoretical calculations and modeling obtained above, which can be used to predict the resonance frequency for certain system parameters, which, in turn, will reduce the time taken to sort through all the parameters of the device in practice to assess the effect of each on any value.

5. Conclusions
Thus, the graphs obtained in theoretical and experimental studies correlate well with each other. The dependences obtained in experimental studies can be used to obtain the necessary resonant frequency using the same probe sensors. The performed simulation allows with a certain accuracy to predict the
resonance frequency for certain parameters of the probe sensor. The results can be used in predicting the dynamic parameters of micromechanical systems when creating gas and biological sensors based on micromechanical structures [6]. The method of focused ion beams makes it possible to fine-tune the resonant frequency of oscillation of cantilevers by changing their geometric parameters.

Acknowledgments
This work was supported by the Russian Science Foundation Grant No. 18-79-00175.

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