Resonance properties of metallic nanocantilevers

Ilya V Uvarov, Victor V Naumov and Ildar I Amirov
Yaroslavl Branch of the Institute of Physics and Technology, Institute of Russian Academy of Sciences, 150007, Universitetskaya Street 21, Yaroslavl, Russia

E-mail: ilnik88@mail.ru

Abstract. Resonant properties of the three-layer metallic cantilevers with 40-120 nm thickness were investigated. Two types of cantilevers were fabricated: Cr/Al/Cr and Ti/Al/Ti. Dependencies of the fundamental resonant frequency and Q-factor on the cantilever length, width and thickness were experimentally obtained. The experimental data analysis and the comparison with the theoretical predictions were performed. Dependence of material properties on the cantilever thickness was not observed. Energy losses in the surface layer of the cantilever were the dominant energy loss mechanism.

1. Introduction

NEMS resonators are used in a variety of technological and scientific applications, such as ultra fast sensors, actuators and signal processing components [1]. With decreasing the resonator size the fraction of surface layer in total resonator volume increases. Atoms of the surface and surface layer of the resonator have altered energy state compared with atoms in the bulk of the material. Therefore surface layer has specific elastic properties which affect the resonance characteristics of the device. In a number of studies the decrease in the Young's modulus of the material with decreasing the thickness of the vibrating cantilever is experimentally observed [2]. Also the rise of energy losses due to surface layer defects is observed with decreasing thickness of the cantilever [3]. However, available experimental data are often discrepant and require verification. In this study we investigate resonance properties of metallic cantilevers having a nano-sized thickness and micron length and width, and hence having ultra high surface area to volume ratio.

2. Cantilever fabrication technology and resonance properties measurement setup

Cantilevers having length from 10 to 100 µm, width from 2 to 10 µm and thickness from 40 to 120 nm were fabricated. To avoid bending of the cantilever by residual stresses a three-layered structure was implemented. Two types of cantilevers were fabricated: Cr/Al/Cr and Ti/Al/Ti, the layer thickness ratio was 1/6/1. The outer layers were made of the material with a higher Young's modulus than the material of the inner layer. They served to compensate for the residual stress gradient occurring in the inner layer of the cantilever during the deposition.

Detailed description of the cantilever fabrication technology can be found in our previous work [4], here the process of fabrication is described briefly. Thermally oxidized silicon wafer (thickness of SiO$_2$ layer was approximately 0.9 µm) was covered by the amorphous silicon (a-Si) sacrificial layer with 2 µm thickness. Next the wafer was covered by the positive photoresist layer, and the cantilevers were patterned by the contact photolithography. Structural layers of Cr/Al/Cr or Ti/Al/Ti with total thickness of 40-120 nm were deposited by the magnetron sputtering method. Then the lift-off process was performed. After that the wafer was covered by the photoresist layer again, the contact pads were
patterned by the contact photolithography. Dry etching of a-Si in SF$_6$ plasma was performed, followed by the wet etching of SiO$_2$ in HF/NH$_4$F solution. Then the Al layer of 100 nm thickness was magnetron sputtered and the lift-off process was performed. Release of the cantilevers was performed by SF$_6$ plasma etching of the sacrificial a-Si layer. The gap between the cantilevers and SiO$_2$ layer was 2 µm. SEM image of the fabricated nanocantilevers is shown on figure 1. Cantilevers had ultrahigh length to thickness ratio that reached record high value of 1500. Fairly wide range of geometric dimensions allowed identifying the features of presented cantilevers.

Cantilever vibrations were excited by the electrostatic force. Tungsten needles were placed to the cantilever contact pad and to the silicon wafer contact pad of the sample (figure 2). The needles were connected to the precision signal generator. Voltage was applied between the cantilever and the silicon wafer, so the cantilever was attracted to the wafer. SiO$_2$ layer served as an insulator. Excitation was performed by AC voltage, DC voltage was not applied. The cantilever was attracted to the wafer twice a period of an applied voltage, so the cantilever vibration frequency was two times larger than the driving signal frequency.

Registration of the cantilever motion was performed by the optical lever method. Laser beam from He-Ne laser was focused by the objective to the cantilever surface. Reflected beam was going to the two-segment photodiode. The dependence of the cantilever vibration amplitude on the frequency of driving voltage was measured. Fundamental resonant frequency and Q-factor of the cantilever were determined from the obtained dependence. Measurements were performed in air at pressure of $10^{-2}$ mbar. Detailed description of the resonance properties measurements method can be found elsewhere [4].

3. Results and discussion

Calculation of the fundamental natural frequency of the cantilever was carried out in accordance with Bernoulli-Euler beam theory, applied to the multi-layer cantilever with length $L$, thickness $t$ and consisting in $z$ direction of $N$ layers with thicknesses $t_i$ and mass densities $\rho_i$ [5]:

$$f_0 = \frac{(1.875)^2}{2 \pi^2} \left( \frac{E (z - z_0)^2}{\sum_{i=1}^{N} t_i \rho_i} \right)^{\frac{1}{2}} \left( \int_{z_0}^{L} E (z - z_0)^2 \, dz \right)^{\frac{1}{2}}$$

where $E$ – Young’s modulus of the material, $z_0$ – coordinate of the neutral axis of the cantilever. For the three-layer cantilever with a layer thickness ratio of 1/6/1 equation (1) may be converted to the following form:
where \( E_{\text{ext}}, E_{\text{int}}, \rho_{\text{ext}}, \rho_{\text{int}} \) – Young’s moduli and densities of the material of external and internal cantilever layers, respectively. Bulk material values of Young’s modulus and density were used in the calculations: \( E_{\text{Cr}} = 279 \text{ GPa}, \ E_{\text{Ti}} = 112 \text{ GPa}, \ E_{\text{Al}} = 70 \text{ GPa}, \ \rho_{\text{Cr}} = 7190 \text{ kg/m}^3, \ \rho_{\text{Ti}} = 4510 \text{ kg/m}^3, \ \rho_{\text{Al}} = 2700 \text{ kg/m}^3. \)

Experimentally obtained values of the resonant frequency of the fabricated cantilevers were in the range of 10-1700 kHz. Analysis of the dependence of the cantilever resonant frequency on the cantilever length showed that there was a qualitative agreement between the experimental data and the calculations. The main reason of the quantitative mismatch was the effect of undercut or, vice versa, the incomplete removal of the sacrificial layer from under the cantilever. This effect changed the effective cantilever length and therefore affected the resonant frequency [6]. Dependence of the resonant frequency on the cantilever width was not observed, which corresponded to the theoretical predictions.

According to the Bernoulli-Euler model, the resonant frequency of the cantilever should vary in proportion to the ratio of thickness to length squared (equation (2)). Proportionality factor is determined by the values of Young's modulus and density of the material. The graph of the dependence of cantilever resonant frequency on \( t/L^2 \) is shown on figure 3. Lines denoted the results of calculations for cantilevers Cr/Al/Cr and Ti/Al/Ti. Experimental values of the resonant frequency, except for the values of the cantilevers made with the undercut more than 1 µm, are also plotted on the graph. Discrepancy between the experimental data and theory does not exceed 10%. It is important that a linear dependence of the cantilever resonant frequency on the thickness to the length squared ratio was observed in the experiment (see figure 3). This indicated that the dependence of the material properties on the cantilever thickness until a thickness of 40 nm was not observed, and the classical beam theory with the bulk material values of Young's modulus and density was appropriate for the calculation of the natural frequency.

Cantilevers had a Q-factor from 100 to 2100. There was a significant variation of Q-factor, but it was possible to identify a number of regularities. First, there was no dependence of Q on the length and the width of the cantilever. Second, the quality factor decreased with decreasing thickness of the cantilever in a manner close to linear. The dependence of the quality factor on the cantilever thickness is shown on figure 4, approximating line is drawn through the mean values. Third, Q-factor of Ti/Al/Ti cantilevers was lower by the order than that of cantilevers Cr/Al/Cr. Fourth, there was a decrease of Q over time: in the case of cantilevers Cr/Al/Cr quality factor decreased by 20% over 3 months in air under normal conditions.

\[
f_0 = \left( \frac{1.875}{16\pi} \right)^2 \frac{t}{L^2} \left( \frac{12.33E_{\text{ext}} + 9E_{\text{int}}}{\rho_{\text{ext}} + 3\rho_{\text{int}}} \right)^\frac{1}{2}
\]
Quality factor of NEMS resonator is determined by several energy loss mechanisms: air damping ($Q_{\text{air}}$), cantilever vibration energy transfer to the substrate through the clamping region ($Q_{\text{clamping}}$), thermoelastic damping ($Q_{\text{TED}}$) and the energy loss due to defects in the bulk ($Q_{\text{volume}}$) and in the surface layer of material ($Q_{\text{surface}}$). These sources operate independently of each other, and the resulting quality factor of the resonator is given by:

$$\frac{1}{Q} = \frac{1}{Q_{\text{air}}} + \frac{1}{Q_{\text{clamping}}} + \frac{1}{Q_{\text{TED}}} + \frac{1}{Q_{\text{volume}}} + \frac{1}{Q_{\text{surface}}}$$

Measurements of resonance characteristics of cantilevers were performed in the intrinsic damping regime, when Q-factor of the cantilever reached a maximum value and was not dependent on the air pressure. Therefore, air damping assumed negligible ($Q_{\text{air}} = \infty$).

Quality factor for the clamping losses in the cantilever with flexural vibrations is determined by the following formula [7]:

$$Q_{\text{clamping}} = \left[ \frac{0.24(1+\nu)}{(1-\nu)\mu} \right] \frac{1}{\left( \frac{L}{t} \right)^3}$$

where $\nu$ – Poisson’s coefficient of the material, $\mu$ – constant, equal 0.336, $\gamma_n$ and $\chi_n$ – constants for the n-th vibration mode (for the fundamental mode $\gamma_n = 0.597$ and $\chi_n = -0.734$). According to equation (4), Q-factor of the cantilever is proportional to the length to thickness ratio cubed. Therefore, the cantilevers having a length to thickness ratio of about 100 should have $Q \approx 10^6$ for the first vibration mode. If the length to thickness ratio is of about 1000, the calculated value of the quality factor is on the order of $10^9$. At the same time, the highest measured Q-factor value of the fabricated cantilevers was of about 2000. Therefore, the energy losses through the clamping point were not the dominant source of energy loss, and the quality factor of cantilevers was limited by other damping mechanisms.

Thermoelastic damping Q-factor is determined by the equation [8]:

$$Q_{\text{TED}} = \frac{\rho C}{E \alpha^2 T} \frac{1 + (\alpha \tau_R)^2}{\omega \tau_R}$$

where $C$ – specific heat, $\alpha$ – linear thermal expansion coefficient, $T$ – absolute temperature, $\omega$ – circular frequency of the cantilever oscillations, $\tau_R$ – relaxation time, given by the equation:

$$\tau_R = \frac{t^2 \rho C}{\pi^2 \kappa}$$

where $\kappa$ – heat conductivity. Q-factor due to thermoelastic damping was calculated in accordance with equation (5). Calculations were performed for the cantilever made of aluminium, having a thickness of 100 nm and a resonant frequency of 100 kHz. The following values of constants and variables were used: $\kappa_{\text{Al}} = 237 \text{ W/(m·K)}$, $C_{\text{Al}} = 930 \text{ J/(kg·K)}$, $\alpha_{\text{Al}} = 23.1 \cdot 10^{-6} 1/\text{K}$, $T = 300 \text{ K}$. For the cantilever with this parameters relaxation time is $1.1 \cdot 10^{11} \text{s}$. At 100 kHz cantilever oscillation period is $10^{-5} \text{s}$. Thus, the relaxation time is much smaller than the oscillation period. Consequently, the thermoelastic damping is small, and, according to equation (5), the Q-factor of the cantilever is $2.09 \cdot 10^8$. For the cantilever made of chromium ($\kappa_{\text{Cr}} = 93.9 \text{ W/(m·K)}$, $C_{\text{Cr}} = 461 \text{ J/(kg·K)}$, $\alpha_{\text{Cr}} = 8.2 \cdot 10^{-6} 1/\text{K}$) relaxation time is $3.6 \cdot 10^{11} \text{s}$ and Q-factor is $1.63 \cdot 10^8$. Thus, thermoelastic damping, as well as the clamping losses, was not the dominant source of energy loss in the fabricated cantilevers.

Energy loss occurring at the defects in the bulk and the surface layer of material are due to the interaction of mechanical waves, propagating in a vibrating cantilever, with various defects. These defects are grain boundaries, foreign atoms in the lattice, surface roughness, surface oxide, various adsorbates, etc. In case of nano-sized resonator the surface layer has sufficient part of the total resonator volume, and considerable part of defects is located in the surface layer. According to the applied model [3], energy loss due to defects in the bulk of the cantilever does not depend on its geometry and defined only by properties of the material. Q-factor due to energy losses at the defects of the surface layer is determined by the following formula:
\[ Q_{\text{surface}} = \frac{t}{6t_s} \frac{E}{E_d^S} \]  

(7)

where \( t_s \) – thickness of the surface layer of the cantilever, \( E_d^S \) – dissipative part of the Young’s modulus of the surface layer. Equation (7) does not allow to calculate the quality factor, because it contains unknown quantities. However, it predicts the dependence of the quality factor on the geometry of the cantilever: Q-factor of the cantilever having nanoscale thickness should decrease with decreasing thickness in a linear manner, and should not depend on the length and width.

On the basis of experimentally obtained dependencies of Q on the geometrical dimensions of the cantilever, it was concluded that the quality factor was mainly determined by the energy losses occurring at the surface layer defects of the cantilever. It was noted above that Ti/Al/Ti cantilevers had a lower quality factor (100-250) than the Cr/Al/Cr cantilevers (900-2100). The difference in Q-factor of Cr/Al/Cr and Ti/Al/Ti cantilevers was presumably caused by high getter ability of titanium. The surface of Ti/Al/Ti cantilever actively absorbed various substances from the environment, which led to the large number of defects and hence a large number of energy loss sources. Chromium does not have high getter ability. The reason of decrease in the quality factor over time most likely was the accumulation of various adsorbates on the cantilever surface. Thus, the experimental data supported the conclusion that the Q-factor of metallic nanocantilevers was mainly determined by the surface layer defects.

4. Conclusions

Resonance properties of the three-layer metallic cantilevers having 40-120 nm thickness and ultra high length to thickness ratio were investigated. Two types of cantilevers were fabricated: Cr/Al/Cr and Ti/Al/Ti. Three-layered structure was implemented to avoid bending of the cantilever by residual stresses. Dependencies of the fundamental resonant frequency and Q-factor on the cantilever length, width and thickness were experimentally obtained. The experimental data analysis and the comparison with the theoretical predictions were performed. Size effects of Young's modulus and density of the material was not observed. The resonant frequency of the cantilevers was determined with a high degree of accuracy by Bernoulli-Euler beam theory for values of Young's modulus and density of the bulk material. The quality factor of cantilevers in the absence of air damping was mainly determined by energy losses occurring at the defects of the surface layer of the cantilever.

The reported study was supported by RFBR, research project No. 14-07-31156 mol_a, by Facilities Sharing Centre “Diagnostics of Micro- and Nanostructures” and by the Ministry of education and science of Russian Federation.

References

[1] Greenberg Y, Pashkin Y A and Il'ichev E 2012 Phys.-Usp. 55 382
[2] Nilsson S G, Borrisé X and Montelius L 2004 Appl. Phys. Lett. 85 3555
[3] Yasumura K Y, Stowe T D, Chow E M, Pfafman T, Kenny T W, Stipe B C and Rugar D 2000 J. Microelectromech. Syst. 9 117
[4] Uvarov I V, Naumov V V and Amirov I I 2012 Proc. SPIE 8700 87000S-1
[5] Sandberg R, Svendsen W, Molhave K and Boisen A 2005 J. Micromech. Microeng. 15 1454
[6] Guillot S, Saya D, Mazenq L, Perisanu S, Vincent P, Lazarus A, Thomas O and Nicu L 2011 Nanotechnology 22 245501
[7] Hao Z, Erbil A and Ayazi F 2003 Sens. Actuators A 109 156
[8] Zener C 1938 Phys. Rev. 53 90