Formation of out-of-plane film micro arch by methods of technological control of internal stress

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Abstract. In this work is presented the analysis of the manufacturing technology of arcuate elastic elements. In the course of the work, the technological problems of the formation of out-of-plane microelectromechanical structures with the use of surface micromachining were studied. Internal stresses were controlled by varying the pressure of the working gas during sputtering. The use of this method allowed forming the arcuate profile of the Cr-Cu-Cr film structure.

1. Introduction
At present, research in the development and fabrication of microelectromechanical systems (MEMS) based on nonlinear effects has become more relevant. This group of devices includes bistable MEMS, in which the elastic suspension with the arcuate profile is the main element. Micro-arched elastic elements were distributed as elements of the RF switching technology, non-volatile memory and Straintronics. Elastic suspension profile shape is defined first mode buckling, thus allowing for existence of two stable states.

Currently the main technologies manufacture arcuate elastic elements is the bulk technology of microsystem technology using deep plasma chemical etching of silicon [1, 2]. This technology allows direct control of the parameters of the electromechanical structure, but has some limitations Another method is the fabrication of micro arches using surface technology, in which the profile of the beam is determined by residual axial internal stresses [3]. The ability to provide a higher density of elements is an advantage of this manufacturing technology.

Much more of the research in this field is directed to a search and selection of materials and their combinations in which internal stresses lead to buckling. Inflexibility in the materials and methods of their application is a disadvantage of this approach, which also affects the flexibility in developing the final device structure. Another approach is the fabrication of out-of-plane film structures using technological control of internal stresses that appear during the formation of structural mechanical layers of films. Such control of internal stresses can be achieved by varying the pressure of the residual pressure during the magnetron sputtering of some metal films [4, 5]. Thus, a number of studies have demonstrated that for some metals sputtering in this way, there is a dependence of the internal stress of the argon residual pressure. This approach can simplify the manufacturing technology of such structures, increase flexibility in the choice of materials and device design, as well as reduce their cost.
2. Experimental results

A study was conducted to identify patterns of internal stresses in multilayer film structures produced by magnetron sputtering. Elastic structures of cantilever and bridge beams were chosen as the object of study. After the multilayer cantilever beam is released from the substrate by removing the sacrificial layer, axial internal stresses cause the occurrence of the deflection moment $M_b$, proportional to the total value of internal stresses and to the formation of a structure with curvature $K$:

$$K = \frac{M_b}{\sum_{i+1} E_i I_i}.$$  \hspace{1cm} (1)

where $E_i$ and $I_i$ are the effective Young’s modulus and the moment of inertia for the $i$ structural layer. This curvature of the mechanical structure will appear regardless of the direction of the acting stresses. Thus, the gradient of the internal stresses of the structural layers of the beam can be determined by its curvature. In turn, the internal stresses of the bridge structure lead to both the stretching of the beam and the change in its resonant frequency, and to its buckling in the case of compression of the beam. Thus, the magnitude of internal stresses $\sigma$ can be determined by multiplying the deformation of the beam $\epsilon$ and the effective Young’s modulus for a multilayer film $E_\Sigma$:

$$\sigma = \epsilon E_\Sigma.$$  \hspace{1cm} (2)

The combined study of these structures allows us to determine the distribution of internal stresses in the structural layers of the film and the direction of their action. A multilayer Cr-Cu-Cr combination deposited on a silicon substrate with an insulating SiO$_2$ layer was chosen as the structural layers of this element. The thickness of the structural layers $t_i$ was 0.1–1–0.4 µm. The beams were released by etching the sacrificial SiO$_2$ layer. These structures were fabricated with different residual argon pressure in the pressure range of 1.2 - 5 mTorr (Figure 1, 2.).

![Figure 1](image1.png)  \hspace{1cm} ![Figure 2](image2.png)

**Figure 1.** Photo of an array of cantilevers deposited at a pressure of Ar 1.2 mTorr  \hspace{1cm} **Figure 2.** SEM image of the bridge array deposited at a pressure of Ar 1.2 mTorr

The elastic parameters of the films were determined using contact methods (on the Hysitron nanoindenter). The obtained values of the Young modulus for the structural layers of Cu and Cr were 60 GPa and 184 GPa, respectively, and differ from typical values by almost two times [3]. This can be caused by a high density of defects and the formation of bulk structural inhomogeneities. The high density of surface defects detected during the study of morphology by SEM (Fig. 3, 4) can indirectly indicate this. The detected imperfections of the structural layers primarily determine the size and type of internal stresses. The obtained values of the elastic parameters were also estimated by resonant methods. The obtained frequency response and phase response are consistent with the results of the finite element analysis [3].
The curvature of the surface of the cantilevers was determined using confocal microscopy (Keyence VK-9700). So on the samples was observed a change in the curvature of the surface and the direction of curvature, depending on the residual pressure. Figures 5 and 6 show that a change in the residual pressure can lead to a significant change in the curvature of the surface.

\[ K = \frac{y_b}{2\sum_{i=1}^{n} t_i} \]  
\[ \epsilon_b = \frac{\sum_{i=1}^{n} E_i \epsilon_i}{\sum_{i=1}^{n} E_i t_i} \]  

where \( \eta_i = 1 + \nu \) is for high strain values.
The strain forces the film cantilever to deflect. The curvature $K$ value and its direction (sign) depend on the deflection of the neutral surface. Cantilever curvature value can be determined proceeding from the following (1)-(4) [6]:

$$K = \frac{3 \sum_{i=1}^{n} E_i t_i (y_i+y_{i-1}-2y_b)(\varepsilon_b-\eta_i \varepsilon_i)}{2 \sum_{i=1}^{n} E_i t_i (y_i^2+y_i y_{i-1}+y_{i-1}^2-3y_b(y_i+y_{i-1}-y_b))}$$

The value of the total internal stresses can be estimated based on the measurements of the beam profile and the relation (2). The study showed that the internal stresses of the chromium layers have a strong dependence on the pressure of the working gas, up to a change in the type of internal stresses (compression / tension) (Fig. 8). Based on the data obtained, the mechanical structures of the micro-arches were fabricated; an example of the profile is shown in Figure 7.

**Figure 7.** The dependence of the internal stresses of the beam structural layers on argon pressure

**Figure 8.** Example of a measured profile of bridge-type structures with a length of 500 µm (pressure Ar 3.4 mTorr)

3. Conclusion
In this paper, internal stresses were investigated and the causes of their occurrence were identified using the Cr-Cu-Cr multilayer film structure as an example. It is determined that the dominant factor in the formation of internal stresses in such layers is the growth of defects and bulk structural inhomogeneities of high density. It is shown that a change in the residual pressure argon during magnetron sputtering leads to a change in internal stresses, up to a change in direction. On the basis of the results were produce arcuate beams applicable for use in bistable MEMS.

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