Electromechanical bending microactuator as optical shutter

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Abstract. This paper presents the design, fabrication methods and characterization of a thin film electromechanical optical shutter. The overlap of the optical channel 1.4 mm high is provided by a multilayer film structure of the cantilever, which profile is determined by the residual internal stresses of the films. In the process of design analysis, the actual parameters of the strained structural layers, the temperature dependence of the curvature, the undamped natural frequencies and the damping parameters of the film cantilever were determined. Correlation of the data shows that the experimental results fit the theoretical data sufficiently closely. The developed control circuit is designed to compensate for the induced dielectric polarization and prevent the control voltage rise and the cantilever sticking effect. The design presented in this publication enables development of a simple and effective electromechanical optical shutter having interruption aperture height which exceeds 1.4 mm.

1. Introduction
The development of microsystem technology leads to a stable miniaturization of sensors and actuators. Thus, with the development of broadband optical networks, micromechanical optical switches and optical switching devices become a frequent use. The vast majority of such like devices operate in-plane [1]. An optical switch represents an optical waveguide arrangement and a micromirror, driven by a micromechanical actuator, switching optical radiation. As the micromirror itself and its displacement are small it causes the search of particular approaches to the formation of a microlens collimating device. Therewith, the fabrication of such microactuators involves expensive processing procedures. At the same time, micromechanical optical switches can be fabricated using surface technology involving basic procedures of microelectronics and optical systems. Suchlike out-of-plane thin film actuators are mostly applicable to HF systems in the form of “zipping” capacitors [2]. The development of suchlike devices in the quality of optical switches requires a particular approach by reason of the necessity of achieving significant out-of-plane displacements of the switching element. Thus, an optical micromechanical shutter should guarantee the overlapping of an optical channel of more than 1-2 mm diameter. The beam diameter is determined by the size of the output section of the collimator lenses, designed to minimize the signal loss. This paper describes the design and fabrication of an out-of-plane active electromechanical element of an optical MEMS shutter of an optical channel with 1.2 mm diameter. The optical signal diameter determines the target displacement of the drive and the overlap area.

2. Development
Using of the bimetallic thin films allows fabricating structures with the high aspect ratio. The formation of such structures is based on internal stresses initiation of film layers $\sigma_l$ during their deposition. The total internal stresses of the multilayer cantilever $\sigma_e$ are determined by the values of the internal mechanical stresses of the layers, as well as by their thickness $t_i$[3]:
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 $K$:

$$K = \frac{M_b}{\Sigma_{i=1}^{n} E_i I_i} = \frac{1}{R}$$ (2)

Herewith, the deviation value for the cantilever is determined by the internal stresses and stiffness properties of the structural layers (Young modulus $E_i$) of Cr and Cu layers, as well as by the geometry of the movable element (inertia values $I_i$ of the corresponding structural layers). Suchlike structure allows interrupting the optical signal with the required cross sectional area.

3. Design

Optical micromechanical shutter includes an optical signal transmission system and an electromechanical shutter system (Figure 1). The beam light is formed by collimating lenses and is interrupted by the microactuator. The actuator structure comprises thin film being the movable electrode, which together with the silicon substrate, forms the drive capacitor. Capacitor electrodes are isolated by the dielectric SiO$_2$ layer.

The cantilever structure represents a multilayer combination of structural Cr and Cu layers with different thicknesses (Figure 2). The actuator profile is determined by the top chrome layer, having high stiffness, and significant internal stresses. The bottom chrome layer is compensation layer. The aimed positioning of the cantilever neutral surface can be obtained by the layers thicknesses adjustment $y_b$:

$$y_b = \frac{\Sigma_{i=1}^{n} E_i t_i (y_i+y_{i+1})}{2 \Sigma_{i=1}^{n} E_i t_i}$$ (3)

Herewith, the cantilever strain $\varepsilon_b$ is caused by the deformation of the structural layers $\varepsilon_i$ due to the internal stresses, and can be defined as follows [3]:

$$\varepsilon_b = \frac{\Sigma_{i=1}^{n} E_i t_i \eta_i \varepsilon_i}{\Sigma_{i=1}^{n} E_i t_i},$$ (4)

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) [3]:

$$K = \frac{3 \Sigma_{i=1}^{n} E_i t_i (y_i+y_{i+1}-2y_b)(\varepsilon_b-\eta_i \varepsilon_i)}{2 \Sigma_{i=1}^{n} E_i t_i [y_i^2+y_{i+1}^2+y_i y_{i+1}-3y_b(y_i+y_{i+1}-y_b)]}$$ (5)

In response to a potential difference applied between the shutter electrodes, an electrostatic load is generated, opposite in sign to the initial deflection moment. The load increase results in cantilever straightening and its fixation on the dielectric layer. To compensate for the induced polarization of the dielectric, the control circuit has been designed, which makes possible to minimize it.
4. Fabrication

The micromechanical actuator is fabricated on the silicon substrate. Thin film cantilever structure is arranged using magnetron sputter deposition of Cr/Cu/Cr layers on the aluminium sacrificial layer. Thin film cantilever is separated from the silicon substrate by the dielectric layer of thermal SiO$_2$. Layer thicknesses of the SiO$_2$ and sacrificial aluminium define the interelectrode gap, and are 0.8 μm each. The thickness of the multilayer thin film structure approximately equals 1.6 μm, where the thicknesses of the cooper layer and top chrome layer equal 1 μm and 0.5 μm, respectively. To reinforce the most mechanically loaded section of the drive, the copper layer is galvanically applied to the cantilever embedding section in the preliminary etched cavity Cr.

The occurrence of the internal stresses is caused by material structure and composition [4]. Moreover, the deposition process itself is prominent in the formation of internal stresses, which results in defect formation in the thin film as well as the initial substrate morphology. The contribution of such stresses is often greater in magnitude and may differ in sign from the temperature stresses. Herewith, the stresses caused by the difference between the thermal expansion coefficients may result in the cantilever deviation from the required shape. However, the bimorph thermal effect can be minimized by applying layers with different thicknesses [4, 5]. It is a challenging task to define the values of the internal stresses, considering all factors involved, at the same time the study of the film structure allow determining film parameters and optimizing the design.

5. Results

The actuator analysis allows determining both the mechanical properties of deposited structural layers and the internal stresses components. Elastic characteristics of structural layers may deviate from the table values due to the structural features of the layers applied by the magnetron sputter deposition. Thus, the Young modulus value, defined using the Hysitron nanoindenter, for Cu and Cr structural layers deviates from the table values and equals 60 GPa and 184 GPa, respectively. The stiffness reduction of metal films is attributed to the deposition modes, which lead to the defect formation in the films. Herewith, the results are confirmed by static measurements of the curvature profile of the film cantilever (Figure 3). The curvature radius of the multilayer cantilever under normal conditions is 1.38 mm. Furthermore, the height of the overlap area of the beam light is 2.5 mm. The internal stresses value for Cu and Cr for magnetron sputter deposition for given thicknesses of structural layers can range within 40-60 MPa and 400-600 MPa, respectively [4]. The internal stresses value in the formed multilayer cantilever can be estimated from the ratio of the theoretical values of the internal stresses of Cu and Cr for the given curvature of the cantilever (Figure 4).

![Figure 3. Profile of the film cantilever 3.5 mm in length; R=1.38 mm](image1)

![Figure 4. Curvature factor as a function of intrinsic stress ratio of chromium and cooper layers.](image2)
The estimation of the resonance frequencies, amplitude-frequency response and circuit phase response allows estimating the volumetric properties of the movable element (mass characteristics) and attenuation parameters. To provide dynamic measurements, the actuator is mounted on piezoelectric vibration drive. The oscillation excitation of the piezoelectric element is provided by alternating voltage in the frequency range from 20 to 1000 Hz. Herewith, the cantilever resonance frequencies were defined using the Laser Doppler Vibrometer (LDV) Polytec close to the free end of the cantilever. The oscillation excitation through external vibration action of small amplitude allows excluding the impact of mechanical “hardening” and electrical “softening” nonlinearities. The absence of nonlinearities in the amplitude-frequency dependence of the film cantilever allows for theoretical estimation of the resonance frequency value, ignoring its curvature [6]. Thus, in the studied frequency range, three resonance peaks were recorded (Figure 5), with frequencies within the ranges of 104-137 Hz, 400-476 Hz, 675-760 Hz, respectively (resonance frequencies scattering is associated with heterogeneous properties of films on samples, positioned in different parts of the substrate). The tests were performed at atmospheric pressure, i.e. under conditions, when the mechanical system has high energy dissipation level. The mechanical quality of the cantilever under given conditions was 19-21, 46-48 and 20-25 for the first, second and third oscillation modes, respectively. Herewith, the experimental results correlate well to the FEM model.

The relation between profile curvature and temperature fluctuation allows estimating the internal stresses arising due to thermal expansion, and undesirable deflections of the cantilever within the operating temperature range. To ensure the efficiency of the optical shutter within the required temperature range, the overlap area should not decrease below 1.4 mm. Measurements of the film cantilever profile were performed using an optical microscope with ambient temperature control within the range of 1-60 °C. The film cantilever curvature variates within 0.57-1.08 mm-1 for this temperature range (Figure 6). This corresponds to beam overlap variation of 1.86-3.35 mm, which is beyond the required deviations.

The opening of the optical shutter is enabled by applying constant voltage difference to the control electrodes. The required control voltage value is in the range from 60 to 100 V. Thereat, the impact of the induced polarization of the dielectric results in a number of undesirable effects. The increase in the voltage, required for opening, is observed, during the cyclic supply of control signals, and sticking of the cantilever. To suppress the undesirable effects associated with the polarization of the separating dielectric, the circuit for supplying the control voltage as packets of alternating voltage was proposed,
designed to depolarize the dielectric. The suggested circuit allows reducing the impact of the induced polarization of the dielectric, thereby, eliminating the increase in the control voltage and the sticking effect.

The experimental static and dynamic characteristics allowed defining the parameters of structural layers, which provided the validation of the theoretical model of the actuator. To validate and optimize the parameters of the device, finite element modeling was implemented.

6. Conclusions
In the process of this research the multilayer film structure of the optical shutter was created, providing to the cantilever the ability to move up to 3.35 mm apart the substrate, which allows overlapping the optical channel entirely. The actual elastic parameters of the structural layers were defined. During the dynamic tests, the natural frequencies and attenuation parameters of the film cantilever were defined. The design parameters of the multilayer structure allow overlapping the optical signal at 1.86-3.35 mm above the substrate surface, which far exceeds the required minimum 1.4 mm.

Correlation of the data shows that the experimental results fit the theoretical data sufficiently closely. The combination of tests performed under the effect of static, dynamic, thermal and acoustic loads, allow defining the mechanical constants of the obtained layers and the mechanical properties of the cantilever. The control circuit was developed to compensate for the induced dielectric polarization, and prevent the control voltage rise and the cantilever sticking effect.

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