

## 336. Thermal mechanisms in electrostatically actuated microelectromechanical structures

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**Abstract:** The paper reports results of the performed research work related to the deformations and stability of Al-Si parallel-plate electrostatic microactuators fabricated on silicon-on-insulator (SOI) wafer and subjected to uniform temperature changes. Presented research includes measurements of the deformation of Si beam with deposited Al thin-film microstructures as a function of temperature changes using Electronics Speckle Pattern Interferometry (ESPI) and a custom-built thermal module that is covered by optical beam splitter window to allow optical access.

**Keywords:** actuator, electrostatic, stress, thermal expansion, thin film, interferometry

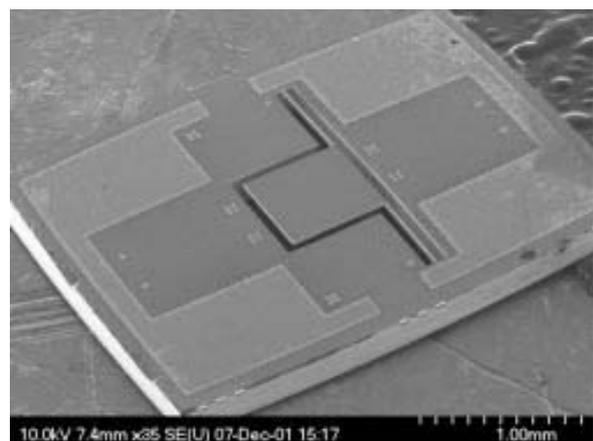
### Introduction

Different principles are used to actuate microstructures in micro(opto)electromechanical systems (M(O)EMS) such as electromagnetic, piezoelectric, thermal and electrostatic. There are many examples of M(O)EMS structures, which are actuated by electrostatic forces and have found various applications ranging from micromotors, comb structures, microswitches to digital micromirror devices, microscanners, optical cross-connects and electrically controlled variable micro attenuators [1-3].

These structures include parallel-plate (deformable beams or diaphragm) as well as torsional actuators. In the latter actuators, as opposed to parallel-plate counterparts, the plates are tilted and an angle  $\alpha$  that is defined between two plates. Such typical electrostatic microactuator with rectangular plates is shown in Fig. 1.

Each electrostatic actuator typically consist of a stiff free standing plate made of two thick layers (metal-insulator), suspended from the bulk by means of two thin hinges. The suspension forms the axis of the plate rotation. The stable metal coating on the plate and hinges, which serve as one electrode (or reflecting surface for MOEMS) can create undesirable temperature-dependent plate curvature due to intrinsic stresses in metal layer and the difference in thermal expansion coefficients of coated metal layer and bulk plate fabricated from a different material. This

problem is particularly severe if the metal coating is applied only to one side of the bulk plate. It is well known that deposited films can exhibit residual stresses [4]. The residual stress in a coating consists in the summation of intrinsic stress and thermal stresses, where the



**Fig. 1.** Scanning electron micrograph of a typical actuator with rectangular plates

former is induced during the film growth process and the latter is caused by mismatch in the coefficients of thermal expansion between the metal thin film and bulk plate.

Therefore, film stresses and thermal expansion coefficients are important for mechanical behavior of M(O)EMS devices. However, only recently the question on the behavior of materials at sub-micrometer scale subjected to uniform temperature changes has been raised.

In this paper we present the results of investigation of thermal effects on the behavior of parallel-plate actuator fabricated on (SOI) wafer. ESPI method for measurement of mechanical and thermal characteristics of deposited thin films is presented and tested experimentally.

### Fabrication of microstructures

In principle, the bulk electrostatic actuator can be fabricated from any material as long as reliability, reflectivity, pull-in parameters and optical flatness requirements are met. Single-crystal silicon (SCS), commonly used in MEMS and MOEMS, is recognized to be the most suitable choice over poly-silicon [5] or electroplated metal [6] due to low intrinsic stresses and excellent surface smoothness. In torsional electrostatic microactuators the material used for hinges is arguably even more important because the bulk plate springs will be constantly twisted and bent. Superior mechanical characteristics make SCS the best candidate for plate hinges. Alternative material such as poly-silicon and metal are poor substitutes because of potential undesirable stresses, hysteresis and fatigue problems. On the other hand, the same material is selected both for the bulk plate and hinges in order to yield a straightforward fabrication process.

SOI wafer is a starting material to create SCS bulk electrostatic actuator with uniform thickness. Parallel-plate actuator with one hinge structure (Fig. 2) was produced using typical lithography, deposition, and deep reactive ion etching (DRIE) techniques as well as silicon wafer bonding and chemical mechanical polishing processes.

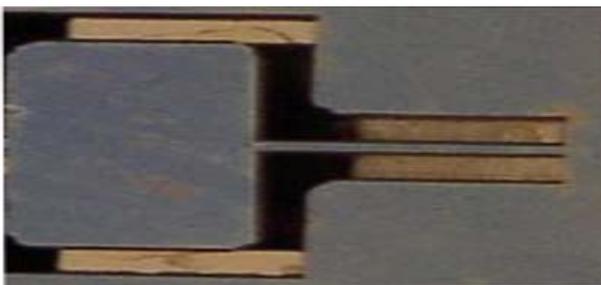


Fig. 2. Parallel-plate electrostatic structure, before depositing metal layer

### Experimental setup

Special interferometric system with thermal module was built for the investigation of thermal properties of the actuator [7]. General view of the interferometer with thermo-module system is presented in Fig. 3. Tested structures were fixed in the thermostat chamber where the temperature is maintained constant or gradually varied with

the help of Peltier elements. Interferometer that is sensitive to out-of-plane surface displacements is used in the system. Optical set-up of the interferometer is given in Fig. 4.

Computer-controlled electronic temperature regulator was developed for the temperature regulation, i.e. keeping it constant or changing according to the prescribed law. Block schematics of the regulator is provided in Fig. 5.



Fig. 3. The general view of the interferometer with the thermostat

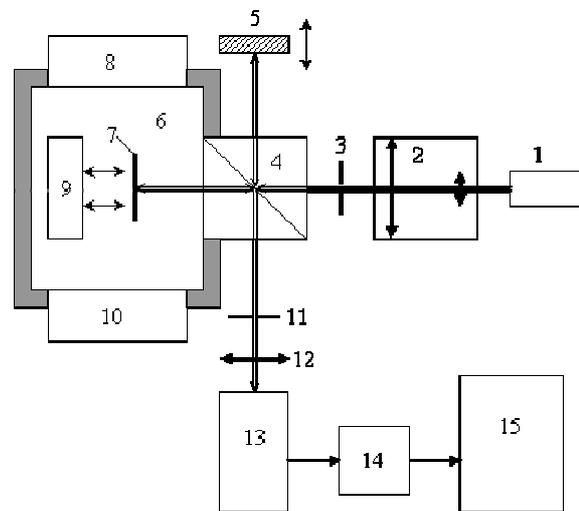
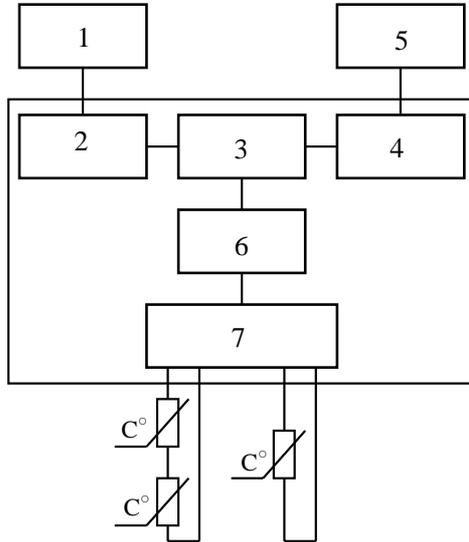


Fig. 4. Optical scheme of the ESPI: 1 – HeNe laser; 2 – beam expander; 3, 11 – apertures; 4 – beam splitter; 5 – reference surface; 6 – thermostat chamber; 7 – specimen; 8 and 10 – temperature support elements (Peltier elements); 9 – system of pattern positioning; 12 – objective-lens; 13 – video camera; 14 – frame grabber; 15 – personal computer

Microprocessor 16F623 is the key element of electronic temperature regulator. The program was written with the help of assembler that performs the main control function according to the appropriate protocols “interacting” with analogue code converter and power unit of Peltier elements, named in the connects with temperature sensors

(thermoresistive ones) that have good thermal contact with the pattern and working surfaces of Peltier elements.

Temperature regulator is controlled within the environment of Visual Basic. Temperature in the thermostat is kept constant or may be varied from -10 to +60 °C according to the given program.



**Fig. 5.** Management of temperature control and support block: 1 – personal computer; 2 – transceiver; 3 – microcontroller; 4 – temperature controller; 5 – Peltier element; 6 – analog-to-digital converter; 7 – amplifier

**Stress calculations and experimental results**

The total stress in a thin film  $\sigma$  is equal to the sum of all external stresses  $\sigma_{ext}$ , intrinsic stresses  $\sigma_{in}$  and thermal stresses  $\sigma_{th}$  [8]:

$$\sigma = \sigma_{ext} + \sigma_{in} + \sigma_{th} \quad (1)$$

Thermal stresses can be expressed as:

$$\sigma_{th} = E_f (\alpha_s - \alpha_f) \Delta T ; \quad (2)$$

where  $E_f$  is Young’s modulus of the film,  $\alpha_s$  and  $\alpha_f$  are the thermal expansion coefficients of the substrate and the film,  $\Delta T$  is the change of the temperature.

The stress of the thin film deposited on a long, narrow and thin substrate is convenient to calculate by using Stoney formula:

$$\sigma_f = \frac{E_s d_s^2}{6(1-\nu)d_f} \left( \frac{1}{R_2} - \frac{1}{R_1} \right); \quad (3)$$

where  $E_s$  is the substrate Young’s modulus and  $\nu$  is Poisson’s ratio,  $d_s$  and  $d_f$  are the thickness of the substrate and the film,  $R_1$  is the radius of the substrate curvature

before deposition of the film,  $R_2$  is the radius of curvature of the structure substrate-thin film.

Variation of temperature of the structure substrate-thin film induces changes in radius of curvature. The difference  $\Delta(1/R)$  (Fig. 6) of the dimension inverse to the radius of curvature is proportional to the thermal stresses upon changes in temperature. Having set the dimension  $\Delta(1/R)$ , thermal stresses can be calculated according to:

$$\sigma_{th} = \frac{E_s d_s^2}{6(1-\nu)d_f} \Delta \left( \frac{1}{R} \right),$$

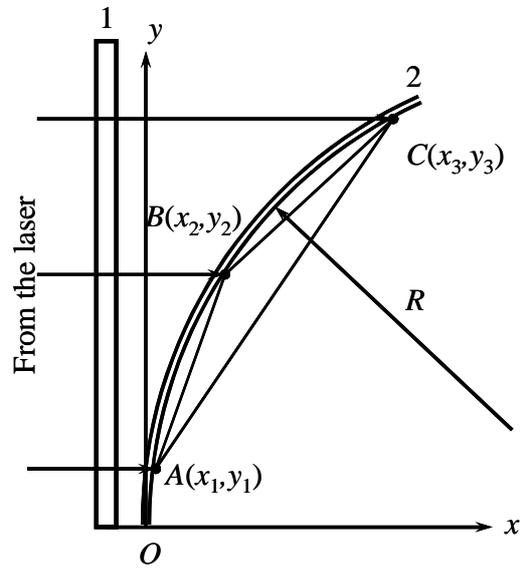
where,

$$\Delta \left( \frac{1}{R} \right) = \frac{\sqrt{4(AB)^2(BC)^2 - [(AB)^2 + (BC)^2 - (AC)^2]^2}}{AB \cdot AC \cdot BC},$$

$$\text{and } AB = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2},$$

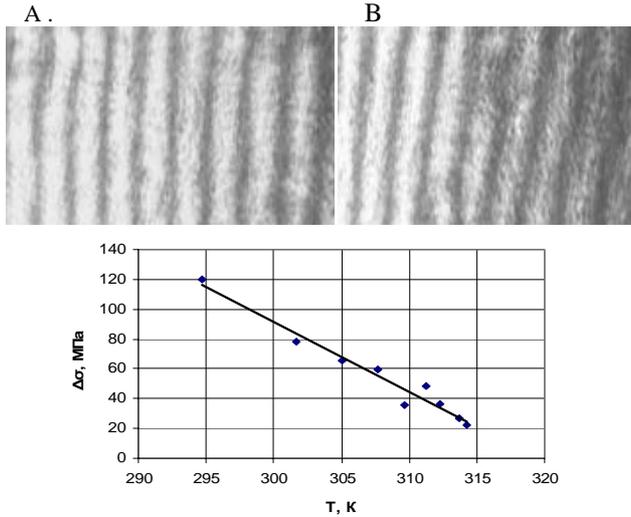
$$AC = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2},$$

$$\text{and } BC = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}. \quad (4)$$



**Fig. 6.** Illustration for the set of plate curvature: 1 - window of interferometer thermostat; 2 - plate

By using aforementioned experimental set-up thermal stresses have been investigated in Si-Al structures by changing the temperature. Experimental results are presented in Fig. 7.



**Fig. 7.** Typical interference patterns and dependences of stresses in Al thin film at temperature A. -  $T = 28,7^{\circ}\text{C}$ , B -  $T = 55^{\circ}\text{C}$

### Analysis

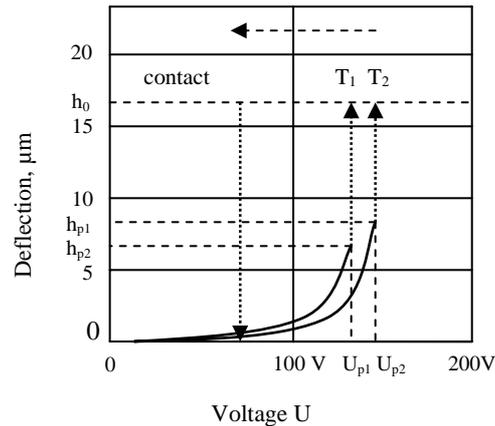
An important parameter that characterizes electrostatic actuators is the pull-in voltage [9]. By increasing the applied voltage on the actuator plates above the certain voltage, the electrostatic torque overcomes the mechanical torque and the movable plate of actuator collapses toward the fixed one thereby achieving the contact. The associated parameters – pull-in voltage ( $U_p$ ) and pull-in deflection ( $h_p$ ), which characterize performance of parallel-plate actuator, can be expressed as [10]:

$$U_p = \left( \frac{24}{27} \frac{EI}{\varepsilon L^3 S} \right)^{\frac{1}{2}} h_0^{3/2}, \quad h_p = 2/3 h_0^{3/2}, \quad (5)$$

where  $EI$  - hinge stiffness,  $\varepsilon$  - vacuum permittivity,  $L$  - hinge length,  $S$  - plate area,  $h_0$  - initial distance between the electrodes.

Fig. 8 shows experimentally obtained curves of plate deflection dependence on DC bias and temperature. Typical pull-in voltage values were found to be in the range of  $160 \div 170$  V depending on the temperature that varied in the range of  $10 \div 55^{\circ}\text{C}$ . The voltage was lower than theoretically expected value mainly because the electric field concentration at the plate edge had been neglected in the analysis.

The stress of Al film deposited on the Si plate varied from 220 to 135 MPa as the temperature increased from  $+10^{\circ}\text{C}$  to  $60^{\circ}\text{C}$  and demonstrate the linear relationship. In the initial stage the tensile stresses in Al film were observed and subsequently decreased after heating since the greater thermal expansion of the Al film removes the tensile stresses. These tensile stresses modify electrostatic field distribution and thereby induce changes in pull-in voltage and pull-in deflection of the electrostatic actuator.



**Fig. 8.** Experimentally determined plate deflection under applied voltage versus measurement temperature, when  $T_2 = 10^{\circ}\text{C}$ ,  $T_1 = 55^{\circ}\text{C}$ , plate thickness -  $20 \mu\text{m}$ ,  $L = 5 \times 10^2 \mu\text{m}$ ,  $S = 1,6 \times 10^3 \mu\text{m}^2$ ,  $\varepsilon = 8,85 \times 10^{-12} \text{Fm}^{-1}$

### Conclusions

The ESPI method has been adapted for testing mechanical and thermal properties of thin metallic and composite films. The proposed system is designed for the measurement of Si plate-thin film thermal stresses and operates together with the thermostat.

The stress changes in thin films has a pronounced effect on pull-in voltage and pull-in distance of electrostatic microactuators and must be taken into account when designing these devices or working in the environment with increased or reduced temperature.

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