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A nickel electrostatic curved beam actuator for valve applications

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Abstract

In this contribution an electrostatic curved beam actuator for microvalve applications is presented. The actuator consists of two layers of nickel consequently plated upon each other. The resulting double-layer cantilever beam has internal stress gradient due to variation of the electroplating process parameters for each layer. By accurate control of these parameters, desired bending heights were obtained. Compared to bimetallic bending actuators, the curvature of the single-metal beam is less dependable on ambient temperature. Thus, more stable performance under changing working conditions was ensured. In order to avoid sticking during the operation of the variable capacitor, stand-off bumps on the back-side of the actuator beam were provided. The actuator was integrated into an active 2/2-microvalve on a silicon substrate.

Keywords: electrostatic actuator; microvalve, electroplating, curved beam

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1. Introduction

Rapid growth of MEMS systems applications demands on adequate efforts to meet strict requirements of the industry. Over the last decades, microfluidic devices and microvalves in particular have become indispensible in automotive, aerospace, healthcare and many other applications [1].

In this work, design, construction and characterization of a nickel electrostatic curved beam actuator are presented. The actuator is an active element of a microvalve intended to be used in a wide range of microfluidic applications. Nickel was chosen for its favorable mechanical properties [2] and simple technological implementation. Electrostatic principle provides good scaling properties to small dimensions, low power consumption, smaller size and higher switching speed [3, 4]. However, it is difficult to design such actuators with large vertical displacements, since there is a quadratic force decrease for increasing electrodes distance [5]. Thus, the controllable displacement is normally limited from one third to one half of the initial gap.

To overcome this obstacle, a curved beam actuator is proposed. Though there have been several different design proposals to the realization of the bending actuator structure [4, 6], we chose a single metal double-layer beam design with internal stress gradient. This approach provides minimal distance between the electrodes at the anchor point to minimize the activation voltage, whereas the gap increases along the curvature and can be made large enough to meet the design requirements. Its technological realization is also relatively simple and efficient. In this

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work, gas flow rates of more than 2000 ml/min must be achieved. Our calculations show that this gap s should be kept around 40 µm above the gas inlet channel nozzle.

Standard silicon wafers and MEMS fabrication processes such as conventional photolithography, electroplating, sputtering and RIE were used. Thus, production costs were minimized. Characterization of the actuator included bending height and bending reproducibility measurements as well as activation voltage tests.

Nomenclature

b_n	width of the beam layer, [m]
c_R	beam bending stiffness, [Nm^2]
d_{eff}	effective distance between electrodes (with isolation layer), [m]
d_n	thickness of the beam layer, [m]
ε_0	permittivity of free space
s	vertical deflection at the free end of the beam, [m]
L_a	length of the beam, [m]
l_f	length of the flat part of the beam, [m]
M_L	internal bending moment, [Nm]
n	layer number
R_b	beam bending radius, [m]
V_{pi}	pull-in voltage, [V]

2. Design and fabrication

2.1. Theory

In order to achieve the desired vertical deflection s at the tip of the actuator we used a single metal double-layer approach. In this case, bending of a beam is caused by difference in internal stresses inside these layers. If there is a tensile stress inside one of the layers whereas the other one has compressive stress, the beam will bend until the internal bending forces become balanced. In equilibrium state the system will have certain bending radius R_b. Knowing this radius it is possible to geometrically estimate the deflection.

Consider a cantilever beam of length L_a consisting of two layers of metal with thickness d_1 and d_2, internal stress σ_1 and σ_2, and Young's modulus E_1 and E_2. Suppose also that the properties of the material remain constant inside the layer. The bending radius is then governed by simple equation [7]:

$$R_b = \frac{c_R}{M_L}, \tag{1}$$

Then one can write that vertical deflection s is

$$s = R_b\left[1 - \cos\left(\frac{L_a - l_f}{R_b}\right)\right] \tag{2}$$

Thereby, deflection depends on the geometrical parameters of the actuator and on the mechanical properties of its material. Since the latter is supposed to be constant, it is possible to change the deflection only by changing length, width and thickness of the beam. Altogether, fifteen design variants were proposed. Thickness was kept constant (20 µm). Length and width were changed in the range from 2.5 mm to 4.5 mm and 0.6 mm to 1.5 mm respectively.

The pull-in voltage V_{pi} needed to attract curved beam to the bottom electrode is determined by [8]:

$$V_{pi} = \sqrt{\frac{c_R}{R_b^2}\frac{d_{eff}}{\varepsilon_0}\frac{1}{b}} \tag{3}$$

2.2. Fabrication

The system elements of the microactuator were fabricated using standard surface micromachining (SMM) techniques dominated by microelectroplating. Fig. 1 represents the technological process of the actuator production.

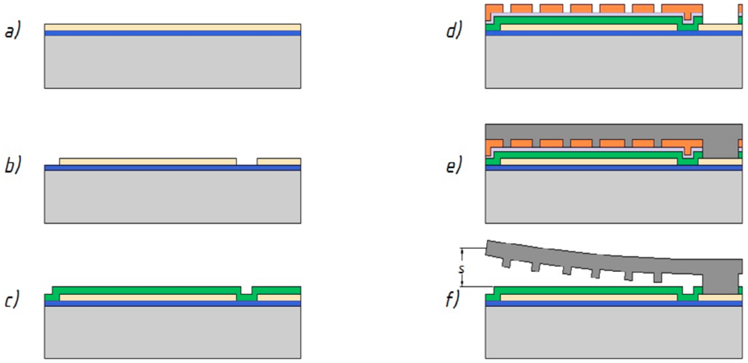

Fig. 1. Technological process of the actuator production

First, a bottom electrode Cr/Au/Cr metallization is sputtered on a standard 380 µm thick oxidized Si wafer (Fig. 1a). Then it is patterned with conventional photolithography and consequently structured using RIE and wet etching (Fig. 1b). After that the electrodes are covered with isolation Si_3N_4 layer using PECVD (Fig. 1c). A thin stop-layer of Ti is then sputtered over the isolation and then 300 µm thick sacrificial layer of Cu is electroplated and structured (Fig. 1d). Finally, two layers of Ni (ca. 2 µm and 18 µm) are electroplated using process current densities of 17 mA/cm^2 and 10 mA/cm^2 respectively to achieve compressive stress in the first layer and tensile stress in the second one. The actuator beam is the released by wet etching of the sacrificial layer (Fig. 1e and 1f). Small lugs that can be seen on Fig 1f represent bumps on a bottom side of an actuator beam. Their function is to minimize electrostatic sticking between the electrodes. REM photo of fabricated active actuator on a microvalve chip is represented on a Fig. 2.

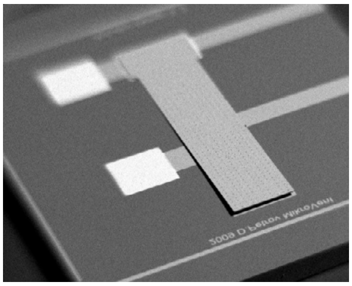

Fig. 2. Microactuator on a microvalve chip (REM representation)

3. Characterization

Optical microscope measurements of vertical deflection were made for all the designs. Their results in comparison with theoretical expectations are shown on Fig. 3. It can be seen that with the increasing design variant number, the deflection of the beam also increases with each consequent group of three variants. The length L_a was kept constant inside these groups.

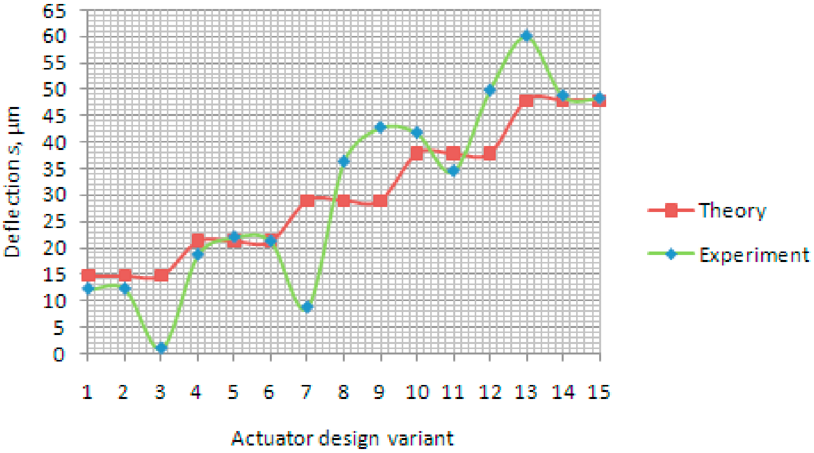

Fig. 3. Theoretical calculations and experimental measurements of vertical deflection *s* as a function of actuator design variant

Deviations from theoretical values can be explained by imperfections of the technological process and by the fact that thickness of the electroplated nickel layers is uneven along the surface of the substrate making some of the beams thicker or thinner than 20 µm. The electrical tests of pull-in voltage V_{pi} show that it lies in the range from 18 to 30 V depending on the design variant. These values meet the specifications.

4. Conclusion

We designed, fabricated and characterized a nickel electrostatic curved beam actuator. The electrostatic principal ensures simple technological implementation and effectiveness of the system operation. Due to use of only one metal, the actuator is less dependent on ambient temperature changes. Characterization mainly proved theoretical expectations of the beam curvature. The actuator can be integrated with the 2/2 microvalve.

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