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Simulation of Metallic MEMS Electrostatic Actuator for Microvalve Applications

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Abstract

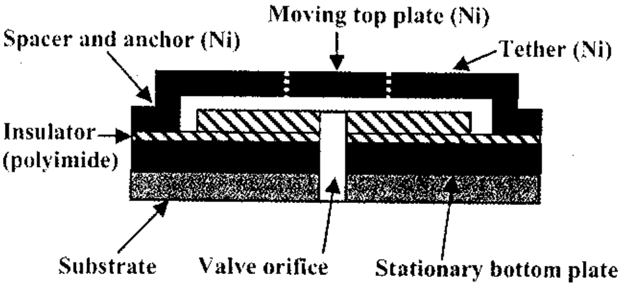
This paper presents the simulation works of novel metallic electrostatic microstructures with various geometry parameters using CoventorWare™ software tools. From simulation of several parallel nickel plate actuators, we observed that the voltage, needed to drive the suspended top plate to move closer to the bottom plate, varies with the length of supporting tethers and the gap between the top and the bottom plates. The longer the tethers, the less voltage demanded. We also found that the bigger the gap, the more voltage needed. The simulation results show that electrostatic actuators requiring driving voltage less than 100 V could be designed with a 3 μm air gap and tethers longer than 400 μm and that the actuators are possibly be used for Braille display applications.

Keywords: MEMS, microfluidic, electrostatic microactuator, metallic microvalve

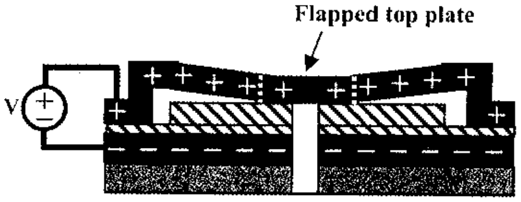
1. Introduction

Microfluidic actuators, especially microvalves, are examples of MEMS (MicroElectroMechanical System) devices that have been increasingly demanded for use in wide range of applications requiring precise control of fluid flow. Such applications of microvalve include biomedical dosing and drug delivery, biochemical reactor, microfluidic mixer and regulator, biological micro-analyzer, as well as pneumatic controller for refreshable Braille display [1-3]. Microvalve is a device that controls the flow of fluids passing through an orifice or microchannel. Fluid flow control could be done in both "ON/OFF" or "variable flow" modes.

Microvalves are based on various actuation principles including heating sealed materials such as pentane, paraffin or hydrogel so that their vapor pressure could be used to push the valve seat that controls the fluid flow [2,4-5]. In some applications such as environmental monitoring, glucose or pH concentrations of solutions could be used to actuate microvalves [6]. Microvalves of this type are actuated when glucose or pH concentrations from the monitored environment slowly diffuse through a porous membrane into a sealed hydrogel filling compartment. The swelling hydrogel creates osmotic pressure to actuate the valve seat. Some microvalves use piezoelectric actuation to push a hydraulic amplified mechanism to actuate the valve seat [7]. Another mechanism is based on electrostatic actuation of a parallel diaphragm and a ground plane [1, 3]. Since electrostatic actuation is one of the most widely used actuation in MEMS, microvalve mechanism in this work will be based on this principle. Electrostatic actuated microvalves conventionally fabricated using semiconductor materials such as polysilicon or silicon nitride as a moving plate that will move downward to close the valve orifice at the substrate when applied by a dc voltage. Among fabrication processes of these microvalves, depositions of both polysilicon and silicon nitride require highly toxic gases and very expensive equipments. In this paper, we propose an electrostatic actuated microstructure using an electroplated metal as a moving top plate instead of conventional expensive semiconductor materials as shown in Figure 1(a). Due to its ease of fabrication, good electrical and mechanical properties, corrosion resistance and smooth surface, nickel is chosen as a plate material.



(a) Metallic microvalve structure.



(b) Valve actuation when a dc voltage is applied.

Fig. 1. Metallic microvalve (a) Structure before applying a dc voltage to the top plate. The valve orifice is opened. (b) During dc voltage application. In this figure downward movement of the top plate is stopped by an insulator. The valve orifice is closed.

The actuator has two metallic plates, the stationary metallic or metal-coated substrate, and a moving metallic top plate. Both conducting plates are separated by an insulator film. The gap height between them is generated by a metallic spacer. This spacer is anchored onto an insulator film. When the bottom plate is fixed connected to the ground, applying a positive voltage to the anchor will create an electrostatic force that pull the top plate downward as shown in Figure 1(b). The insulated slab placed on top of the bottom plate is used to prevent short circuit situations and to reduce the displacement required in order to close the valve orifice. The displacement Z, in which the top plate is pulled down, is given by the well known Eq.(1).

$$Z = \left(\frac{A\varepsilon}{2kh^2}\right)\cdot V^2 \qquad (1)$$

where:

Z is a displacement of the top plate (m)
k is a spring constant of the tether (N/m).
h is an original gap distance between the plates (m).
ε is a dielectric constant of the (air) gap (F/m),
A is an area of the top plate (m^2), and
V is an applied voltage (V).

In order to identify dependencies of the top-plate movements with geometric parameters such as the length of the tether linking the top plate with the spacer, the original gap distance between both plates, and the applied voltage, simulation works for various structure configurations were carried out using CoventorWare™, a commercially available MEMS simulation tools based on finite element analysis.

2. Structural model

An electrostatic parallel plate structure as shown in Figure 2 has an electroplated nickel layer as a fixed bottom plate. An insulated spacing layer with a thickness h is placed in between the top and bottom nickel plates. The 1 µm thick, 240x240 µm top plate is suspended in the air by four 30 µm-wide tethers. Due to layout limitations of the simulation tools the top plate and tethers are modeled so that they are attached on an insulated spacer instead of nickel spacers and anchors as in actual model shown in Figure 1(a). In addition, the valve orifice underneath the top plate is not taken into account in the simulations. Study of the presence of valve orifice and the influence of air flowing thru it will be left as future works.

Solid structural models of 400 or 820 or 1,120 µm-long tether, and 1 or 2 or 3 µm-high air gap, were constructed, meshed and simulated with various positive dc voltages applied to the top plate, while the bottom plate is grounded. To determine the maximum applied voltage that causes the top and bottom plates to touch each other (short circuit situation), the simulations were done without inserting a slab of insulated stopper discussed earlier. Once the short circuit voltage is found for each structure, a slightly higher voltage will be applied to confirm that the top plate will press firmly on the bottom support structure (simulation result at this point will not be realistic since the pulled down top plate will extend below the bottom plate, in which case is not possible in real life situation)

3. Simulation results

After the structural models have been simulated, we found relations between geometry parameters and the required voltage applied to the top electrode, which are graphically shown in Figure 3, 4, and 5. All of these three figures shows similar trend of data. The main difference is the numerical values of the required apply voltage. We observed that actuators with longer tethers demand less voltage in order to move downward. For tethers of same length, the smaller the air gap, the less voltage it needs to pull the top plate down.

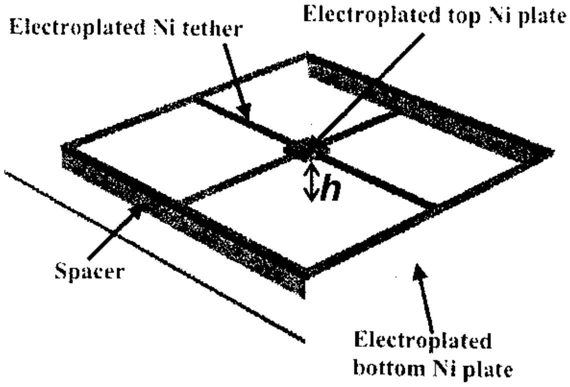


Fig. 2. Structural model of a parallel-plate electrostatic actuator made of nickel. Both plates are apart with a distance h defined by the thickness of the spacing layer.

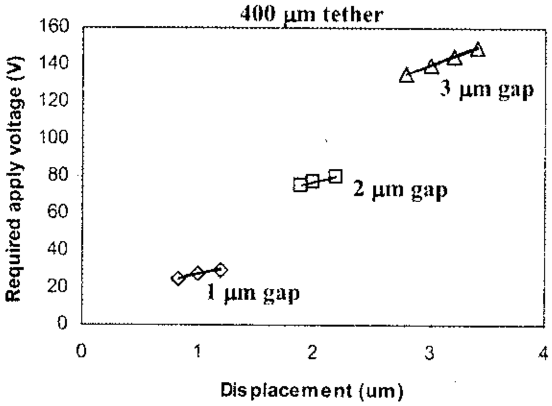


Fig. 3. Vertical displacement and the required apply voltage of electrostatic actuators with 400 µm-long tether and 1 or 2 or 3 µm-high air gaps.

In real structure of actuators, the top plate is not allowed to touch the bottom plate to prevent shot circuit situation. If the bottom plate is coated with a thin passivation material, the top plate can be applied with a voltage beyond the touching voltage, as shown in Table 1, in order to create a firm contact between the plates. For long-tether actuators (greater than 800 µm), it can be seen that the top plate may be pulled downward across a 1 µm-gap to virtually touch the bottom one by applying a voltage less than 10 V. However, fabricating such a structure with large area and only 1 µm gap may be difficult. To avoid this difficulty, an easier to realize structure of 3 µm-gap and tethers longer than 400 µm may be used with touching voltages less than 100 V. In addition to quantitative simulation results, movements of the top plate can also be visualized so that the structures and their expected functions can be more comprehensively understood. Figure 6 shows a visualized vertical displacement of a simulated electrostatic actuator.

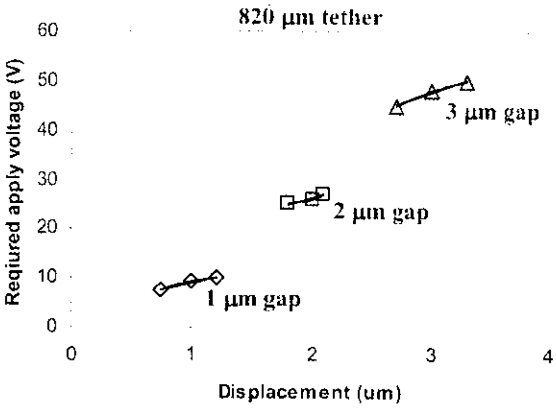


Fig. 4. Vertical displacement and the required apply voltage of electrostatic actuators with 820 µm-long tether and 1 or 2 or 3 µm-high air gaps.

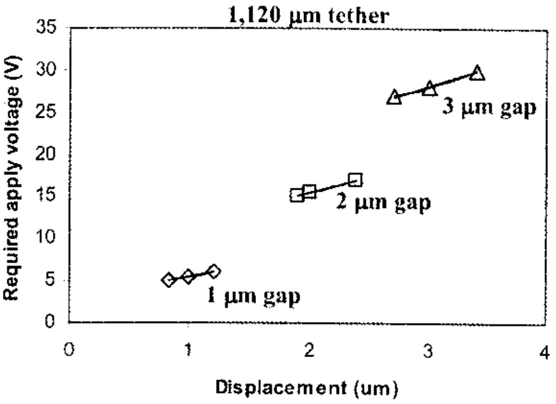


Fig. 5. Vertical displacement and the required apply voltage of electrostatic actuators with 1,120 µm-long tether and 1 or 2 or 3 µm-high air gaps.

Table 1. Simulated apply voltage that pulls down the top plate so that it virtually touches the bottom one.

Tether length (µm)	Original gap height (µm)	Touching voltage (V)
400	1	27
	2	77
	3	140
820	1	9
	2	26
	3	48
1,120	1	6
	2	16
	3	28

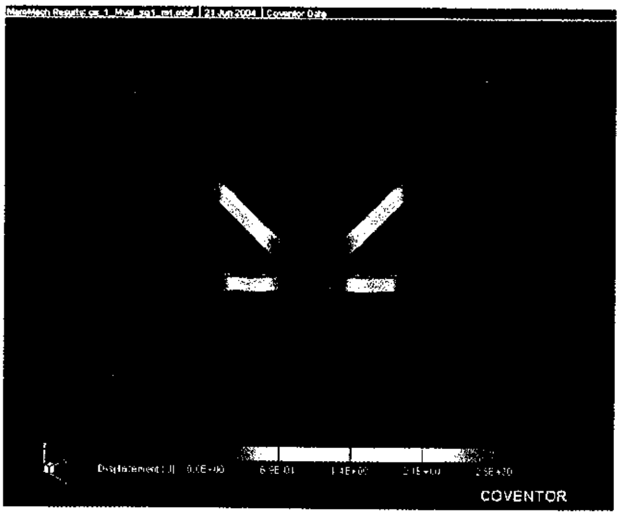


Fig. 6. Visualization of vertical displacement of the top plate at 135 V. The actuator has a 1 µm-thick and 240x240 µm-wide nickel top plate, 400 µm-long and 30 µm-wide tethers. In this photo, the vertical scale was exaggerated at 50x so that the 2.8 µm displacement along the 3 µm-gap could be observed.

4. Discussion

From the simulation data, it can be summarized that driving electrostatic actuators made of nickel requires reasonable low driving voltage. Very low voltage actuation might be realized if stiction problems are manageable. Utilizing metallic surface micromachining techniques, especially metal electroplating processes, is a promising approach to realize low-cost microvalve structures.

Simulation works reported in this paper have demonstrated the possibility of such devices. However, the practical issues that may arise when we pursue this approach include adhesion problem of the plating base layer on which electroplated structures will be deposited, as well as stress problem in electroplated metal films.

In order to find out if the metallic electrostatic actuators proposed in this paper, will be able to work as a microvalve in our interested application, *i.e.*, in a refreshable Braille display pneumatic valve that supply air pressure to a tactile Braille dots, we need to determine whether our structures can be actuated to overcome the differential air pressure of at least 27.6 kPa [3]. Inside the microvalve, the force generated by air molecules moving thru an orifice could be calculated from the differential pressure across the two sides of the valve, provided that the area of the orifice is known. For a valve orifice with 70x70 µm opening, the force generated by the flowing air, estimated from Eq. (2), is approximately 136 µN.

$$F = PA \qquad (2)$$

where:

F is a force generated by the moving air passing thru the valve orifice (N),

P is a differential pressure of gas passing thru the valve orifice (N/m^2),

A is an opening area of the valve orifice (m^2).

To move the top plate down to the orifice opening, the electrostatic force generated by the supplied voltage must overcome the net resisting force, the sum of forces generated by the air movement at the valve orifice and the pull-back force of the tethers. The pull-back force of the tethers could be calculated by first calculating the spring constant k of the structure using Eq. (1). The pull-back force is then obtained by multiplying the spring constant with the top plate displacement. The estimated net resisting forces of various structures could be found in Table 2.

Table 2. Approximate net resisting force needed to be overcome in order to pulls down the top plate to close a 70x70 μm valve orifice thru which the air of 27.6 kPa differential pressure passing.

Tether length (μm)	*Original* gap height (μm)	*Net resisting* force (μN)
400	1	323
	2	511
	3	698
820	1	154
	2	173
	3	192
1,120	1	143
	2	150
	3	158

When the air with differential pressure is applied across the orifice, the top plate of the structure with longer tethers will move upward to a higher height more easily resulting in a larger original gap h between the plates. Hence, the apply voltage required to pull the top plate downward need be increased. To this end, the structures with longer tethers will experience larger original gap height and require higher apply voltage to pull down the top plate. This is in contrast with behavior found in the case of purely electrostatic driving without applying the differential air pressure mainly simulated in this paper. In order to obtain the results closer to real situations, more simulation works that take the differential air pressure into account need be performed.

5. Conclusions.

We have carried out electrostatic simulations of several novel metallic electrostatic actuators made of nickel. The dependencies of geometry parameters, displacements and driving voltages were roughly identified to evaluate the potential of utilizing the structures as microvalve for low-pressure and low-cost pneumatic applications. It was found that the driving voltage could be reduced using longer tethers and smaller air gap. In addition, Visualization tools had been used to demonstrate the concept comprehension of such actuators.

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