# A Vertical Electrostatic Actuator with Extended Digital Range via Tailored Topology

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# Abstract

We describe the design, fabrication, and testing of an electrostatic vertical actuator that exhibits a range of motion that covers the entire initial gap between the actuator and substrate and provides controllable digital output motion. This is obtained by spatially tailoring the electrode arrangement and the stiffness characteristics of the microstructure to control the voltage-deflection characteristics. The concept is based on the electrostatic pull down of bimaterial beams, via a series of electrodes attached to the beams by flexures with tailored stiffness characteristics. The range of travel of the actuator is defined by the post-release deformed shape of the bilayer beams, and can be controlled by a post-release heat-treat process combined with a tailored actuator topology (material distribution and geometry, including spatial geometrical patterning of the individual layers of the bilayer beams). Not only does this allow an increase in the range of travel to cover the entire initial gap, but it also permits digital control of the tip of the actuator which can be designed to yield linear displacement - pull in step characteristics. We fabricated these actuators using the MUMPs surface micromachining process, and packaged them in-house. We measured, using an interferometric microscope, full field deformed shapes of the actuator at each pull in step. The measurements compare well with companion simulation results, both qualitatively and quantitatively.

Keywords: electrostatic actuator, digital movement, MEMS, range of travel, bilayer beam, pull in step

# 1. Introduction

Actuators are a principal component of a large class of microelectromechanical systems (MEMS). Micromechanical electrostatic actuation is very attractive because of the relative ease of fabrication via thin-film technology. However, electrostatic actuators that are able to generate relatively large vertical displacements (normal to the substrate) are difficult to realize. The controllable range of travel is usually limited to one third to one half of the initial gap. Many applications, especially optical MEMS,<sup>1</sup> would benefit greatly by the availability of vertical actuators that extend the range of motion.

Several methods have been proposed to extend this range of motion. Legtenberg et al.<sup>2</sup> described an electrostatic actuator consisting of a laterally compliant cantilever beam and a fixed curved electrode where the beam is bent around the fixed electrode. Chan and Dutton<sup>3</sup> presented a design that employs a series of capacitors to extend the range of travel to 60% of the initial gap. Hung and Senturia<sup>4</sup> described a design with leverage bending. The above efforts have been focused on overcoming the conventional pull in limit; to the best of our knowledge no work has been reported to provide controllable digital output motion.

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In this paper we prescribe a unique microstructure that exhibits a range of motion that covers the entire initial gap (between the actuator and substrate) and provides controllable digital output motion. This is obtained by spatially tailoring the electrode arrangement and the stiffness characteristics of the microstructure to control the voltage-deflection characteristics, while at the same time providing digital output.

# 2. Concept

The range of travel of the actuator is defined by the post-release deformed shape of the bilayer beams, and can be controlled by a post-release heat-treat process combined with a tailored actuator topology (material distribution and geometry, including spatial geometrical patterning of the individual layers of the bilayer beams).

The electrostatic actuator concept is based on the electrostatic pull down of bimaterial beams, via a series of electrodes attached to the beams by flexures with tailored stiffness characteristics. A schematic diagram of one realization of the actuator is shown in Fig. 1 (a). Two bilayer beams are cantilevered from an anchor above the substrate and are connected to each other by flexures and plates which serve as electrodes. In this design, eight flexures connect four plates to the two bilayer beams; the plates are numbered from one to four from the cantilevered end of the beam. Underneath each plate, a polysilicon electrode is deposited on the substrate to which voltage will be applied for actuation. Of course, the number of plates (electrodes) and their shapes, sizes, and locations are design variables.

In the design to be fully described later, the bilayer beams (350  $\mu$ m long × 25  $\mu$ m wide) consist of gold (0.5  $\mu$ m thick) and polysilicon (1.5 $\mu$ m) layers. Due to internal stresses induced during fabrication, including those due to thermal expansion mismatch between gold and polysilicon, the bilayer beams bend up from the substrate after release; we refer to this as a positive curvature. The magnitude of this deformation, which we will characterize by either the curvature or tip deflection of the beam can be controlled by a post-release heat-treat process, and the spatial geometrical patterning of the gold film on the polysilicon film, which will be discussed in the next section. This initial deformation provides the initial gap, and thus defines the range of travel of the actuator. The flexures and plates are made of a single layer of polysilicon (1.5  $\mu$ m thick). The flexures consist of very thin (about 4  $\mu$ m wide) bending strips. To actuate, we first apply a voltage to the electrode beneath the first plate (that closest to the cantilevered end). At a critical applied voltage the first plate pulls in completely to the substrate and pulls the bilayer beams down via the flexures, decreasing the tip height of the actuator. Similar actuation processes occur when voltages are subsequently applied to the other electrodes in sequence from two to four, and the plates are pulled down sequentially. The result is that four pull-in steps are realized, which result in digital output of the displacement at the tip of the actuator. Figure 1 (b) shows the side view of the actuator at the initial and each pull in steps. Stepwise pull-in allows the range of travel to increase to the entire initial gap of the vertical electrostatic actuator.



Figure 1: Digital electrostatic vertical actuator designed to increase the controllable range of motion and to provide a controllable digital movement output: (a) schematic diagram illustrating components; (b) side view of the actuator at the initial and subsequent pull-in steps.

## 3. Design, Analysis, and Fabrication

#### 3.1 Initial Gap/Range of Travel

The range of travel of the actuator is defined by the initial deformation of the bilayer beam and can be controlled by a post-release heat-treat process and the spatial geometrical patterning of the gold film on the polysilicon film. To illustrate, Fig. 2 shows the measurements of curvature vs. temperature for gold (0.5  $\mu$ m thick) / polysilicon (1.5  $\mu$ m thick) 300  $\mu$ m × 50  $\mu$ m beams upon uniform heating and cooling cycles (a heat –treat process) over a temperature range from room temperature to 100°C – 275°C.<sup>5</sup> This temperature range encompasses the temperature excursions that are expected during many post-processing and packaging steps. During operation there are two key parameters that are strongly impacted by this cyclic thermal behavior: the linearity of the curvature developed as a function of temperature, and the curvature at room temperature (or any other specified temperature) which sets the reference state for the device. As shown in Fig. 2, the linearity can be ensured to a large degree over a certain temperature range by cycling the microstructure to 200°C, it can be expected to subsequently deform linearly over a temperature range with a maximum temperature less than 200°C. Although beyond the scope of this study, the complete characterization of the deformation-temperature behavior requires the consideration of the rate of temperature change, and in particular, the length of time the microstructure is held at the elevated temperature.



Figure 2: Curvature vs. temperature for gold (0.5  $\mu$ m thick) / poly2 (1.5  $\mu$ m thick) 340 $\mu$ m × 50  $\mu$ m beam microstructures.

The room-temperature deformed shape sets the initial gap of the electrostatic actuator. It can be tailored by a combination of the structural geometry and the heat-treat process parameters. To illustrate, consider the gold/polysilicon beam microstructure in the actuator. We will describe how one can tailor the heat-treat process and the topology (material distribution and geometry) to meet two different initial gap requirements. For the purposes of this discussion we use the data in Figs. 2 and 3. The generalization to other gap requirements follows along the same lines.

- Assume that we want the initial tip deflection to be 25  $\mu$ m, which is larger than the tip deflection after release. In order to obtain the desired tip deflection, first let us calculate the curvature required to yield a 25  $\mu$ m tip deflection for the L = 350  $\mu$ m gold (0.5  $\mu$ m thick) / polysilicon (1.5  $\mu$ m thick) beam. For a beam with uniform curvature, the tip deflection  $\delta$  is related to the curvature  $\kappa$  simply as  $\delta = \frac{1}{2} \kappa L^2$ , where L is the length of the beam. For L = 350  $\mu$ m and  $\delta = 25 \,\mu$ m,  $\kappa = 408 \, \text{m}^{-1}$ . Now from Fig. 2, in order to obtain a room-temperature curvature of 408  $\text{m}^{-1}$ , the beam must be heated to about 120 °C and cooled to room temperature. After this heat-treat process, the deformation as a function of temperature will then be linear as long as the temperature does not exceed 120°C. Suppose that the actuator must undergo a post-release process such as wire bonding. If the wire bonding temperature is below 120 °C, then no additional unwanted deformation will occur during wire bonding. The same argument applies to any other packaging processes so that the deformation experienced during the packaging processes will be linear theremoelastic and result in no permanent deformation.
- Suppose, however, that the device application requires that after packaging, the beam have a curvature of 200 m<sup>-1</sup> (corresponding to the tip deflection of 12 µm), and that the packaging process exposes the actuator to a temperature of 120°C. If one simply carried out the process as described above, upon return to room temperature the curvature would be about 400 m<sup>-1</sup>, rendering the device unusable. The challenge is then to design the geometry, for example the layout of the gold film on the polysilicon, so that the room-temperature curvature after packaging is still acceptable. In the present example this could be accomplished by covering only part of the polysilicon beam with gold. The results of such an approach are shown in Fig. 3 where the thermoelastic slope dk/dT is plotted as a function of the fraction of the beam that is covered with gold. Both analytical predictions and measurements are shown. In principle, one could use the results of Figs. 2 and 3 to design the shape of the cantilever. For the example here, suppose we want to ensure linear thermoelastic deformation between 140°C and room temperature, so the temperature change is 25°C 140°C = -115°C. Thus dk/dT = 200 m<sup>-1</sup>/115°C ≈ 1.74 m<sup>-1</sup>/°C. According to Fig. 3, the coverage of gold will be approximately 20% of the polysilicon.



Figure 3: Slope of the curvature vs. temperature change as a function of gold film width for a strip patterned beam. Filled circles are measurements, open circles are finite element calculations, and the solid line is an analytical estimate<sup>5</sup> based on linear plate theory.

#### **3.2 Electrostatic Actuation**

Consider a conventional cantilever beam electrostatic actuator. The basic idea is that a potential difference is applied across the gap between the bottom of the beam and an electrode on a substrate beneath it. This generates an electrostatic force that pulls the beam toward the substrate. The actuator characteristics (voltage vs. deflection) are highly nonlinear due to the competing effects of the nonlinear electrostatic forces and the linear mechanical restoring forces. The former arise because the electrostatic force acting on the beam varies as  $1/\delta(x)^2$  where  $\delta(x)$  is the distance between the substrate and the point on the beam at the lateral position *x*. As the beam deforms,  $\delta(x)$  decreases and the electrostatic force increases nonlinearly. At some critical applied voltage the system becomes unstable and the beam *pulls in* completely to the substrate. Almost all electrostatic actuators of this type have been designed based on simple perturbations of the simple cantilever. In addition to the highly nonlinear voltage-deflection characteristics, the actuator is analog in nature.

Our objective is to achieve a step-wise pull in, leaving the tip up and pulling in the actuator from the fixed end. This is not possible for a single solid beam. Our approach to achieve such pull-in characteristics is to balance the nonlinear electrostatic forces with nonlinear mechanical restoring forces by spatially tailoring the distribution of both the structural material (and thus stiffness) and the electrodes. With our actuator design, both the restoring electrostatic and mechanical forces are impacted by the design variables. The electrostatic forces are modified by tailoring the distribution of the electrodes and the overlap area between the plates and electrodes. The mechanical restoring forces are modified by the tailored topology, i.e., the flexure geometry and layout, and the geometry of the bilayer beams.

To illustrate how the stiffness/flexibility are modified, a simplified design is shown in Fig. 4 (a), where each plate is connected via two flexures to the bilayer beams. We assume that for each plate, the spring constant is only related to the flexures connected to it and the bilayer beams. The electrostatic force acting on the plate is transferred to the two flexures connected to the plate, and via the flexures, the electrostatic force is transferred to the cantilever bilayer beams as an intermediate load. A schematic diagram is shown in Fig. 4 (b), where  $F_i$  (i = 1, 2, 3, and 4) represents the electrostatic force acting on the plate that is transferred to the flexures and the bilayer beams. Therefore for each plate, a spring constant  $K_{equiv}$  can be calculated as shown in Fig. 4(b) where  $K_{flexure}$  represents the spring constant of the bilayer beam with intermediate load.  $K_{flexure}$  will vary for different flexure designs, and  $K_{beam}$  will vary as the intermediate load position changes, i.e., as the beam is pulled in.



Figure 4: (a) Top view of the actuator design; (b) schematic showing the dominant stiffness characteristics of the actuator.

#### 3.3 Other Features of the Actuator

Besides the features discussed in section 3.1 and 3.2, the actuator presented in this paper has the following additional features:

- As the plates are sequentially pulled down, they pull down the bilayer beam via the flexures and thus decrease the tip deflection. Without this tailored topology, it is impossible to achieve the stepwise pull in for a solid beam. By simply modifying the stiffness of the bilayer beam, for example, by making some part of the beam flexible, stepwise pull in can be achieved to some degree, but the controllability is very limited and the freedom to modify the tip response characteristics is compromised.
- The topology can be tailored to yield desired digital output characteristics. For example, the topology can be tailored to yield a linear tip displacement voltage relationship. Once the tip displacement response characteristics have been identified for a particular device or grouping of components based upon the overall MEMS design criteria, an actuator can be constructed to achieve those characteristics by spatially tailoring the topology, i.e., the material geometry and layout.
- Although the microstructures described so far were designed to have four pull-in steps, the number of the pull in steps, which is determined by the real application, can be easily changed.

### 3.4 Simulated Response

We simulated the coupled electromechanical behavior of the actuator using a fully coupled simulator (MEMCAD 4.8) that couples boundary element electrostatics and finite element structural mechanics. Both the gold and polysilicon are modeled as linear thermoelastic with isotropic material properties. Input parameters are  $E_p=163$  GPa,  $v_p=0.22$  (in line with many measurements over many MUMPS runs),<sup>7</sup>  $E_g=78$  GPa,  $v_g=0.42$ .<sup>8</sup> The thermal expansion coefficients of the materials are assumed constant and their average values over the temperature range considered are  $\alpha_p=2.8\times10^{-6}/^{\circ}$ C, and  $\alpha_g=14.4\times10^{-6}/^{\circ}$ C.<sup>8</sup> Here and throughout the subscripts *p* and *g* denote polysilicon and gold, respectively. Typical finite element meshes for the actuator microstructures contained elements with a characteristic dimension of about 10  $\mu$ m, a size that was chosen after a careful convergence study with mesh size.

The complete calculations consist of two parts. First, the thermomechanical deformation with uniform temperature change is computed using the MemMech solver. The second step of the calculations is the electrostatic pull in using the CoSolve\_EM solver with the voltage applied to the appropriate electrodes at each pull in step. The starting point for the second step is the end point of the first step. Results from simulations as just described were used to tailor the layout and geometry to yield specified actuator deformation response characteristics. Specifically, we attempted to obtain a linear pull-in vs. tip displacement response.

# 3.5 Fabrication

We fabricated actuator designed as described above using the commercially available Multi-User MEMS Process (MUMPs).<sup>9</sup> Specifically they are fabricated using the MUMPs 41 surface micromachining process, and then packaged them in-house. The maximum temperature experienced by the actuator during packaging was about 75°C. We then measured, using an interferometric microscope, full field deformed shapes of the actuator at each pull in step. Details regarding the measurements are described elsewhere.<sup>10</sup>

# 4. Results and Discussion

#### 4.1 Single Actuator Performance

Figure 5 shows a scanning electron image of an actuator designed to provide linear tip deflection – pull-in behavior. Figure 6 shows the measured full field deformed shapes of the actuator at the initial position after packaging, and at each

subsequent pull in step. The measured pull in voltages for each pull in step are 46.6v, 38.2v, 9.4v, and 11.2v. Compared with the simulation, the measured pull in voltages are about 10 to 15 volts lower.



100 µm

Figure 5: SEM image of the electrostatic actuator designed to provide linear digital of tip deflection vs. pull-in step characteristics.



Figure 6: Measured deformed shapes of the actuator at the (a) initial, (b) first, (c) second, (d) third, and (e) fourth pull-in step, respectively.

From the measurements of the full-field deformed shapes, we determined the tip deflection relative to the fixed end; the results are plotted in Fig. 7 vs. the pull-in step. Figure 7 also shows the initial tip deflection and that at the first three pull in steps from the simulation. The measurements compare well with the companion simulation results. The tip deflection

at the fourth pull in step is not plotted in Fig. 7 because it was not designed to follow the linear relationship exhibited during the previous steps. A linear fit to the measurements shows the excellent linearity of the response.



Figure 7: Tip deflection vs. pull-in steps from both the measurements and simulations of the actuator shown in Figure 5.

In Fig. 8 we plot the surface profile relative to the height of the fixed end along one of the bilayer beams at the initial, fist, second, and third pull in steps. The solid lines are measurements and the open circles are simulation result. The two significant bumps in each experiment result are due to the conformal surface micromachining process, where two wires connected to two electrodes lie beneath the bilayer beam. This can be seen clearly in both Figs.5 and 6. At the initial position, the bilayer beam deforms due to the internal stresses only, therefore the curvature is uniform along the beam. When the first plate (that closest to the cantilever end) is pulled down, the bilayer beam deforms due to the combination of the internal stress and the electrostatic force. As a result, the curvature is not uniform over the part of the beam extending from the fixed end to the first electrode; that part of the beam, about  $45\mu$ m from the fixed end, is relatively flat. Similarly, in the second and third pull in steps, the length of the relatively flat part increases to about 120 µm and 190µm, respectively. For all pull-in steps, the measurements agree well with the simulation results.



Figure 8: Surface profile along one bilayer beam from both the experiment and simulation results at the initial, first, second, and third pull-in steps from top to bottom, respectively. Solid lines are measurements and open circles are simulation results.

#### 4.2 Actuator Assemblies that Provide 2-D and 3-D Adjustments – Micromirror Applications

The controllable and digital character of this actuator offers the ability to operate it in an open-loop control mode, a significant advantage, particularly in the common situation where arrays of multiple actuators exist. For example, this digital electrostatic vertical actuator can be combined with a mirror or a mirror array with applications in optical switching. Work along these lines is underway and will be presented elsewhere.

### 5. Summary

We designed and tested an electrostatic vertical actuator that exhibits a range of motion that covers the entire initial gap between the actuator and substrate and provides controllable digital output motion. The range of travel of the actuator is defined by the initial deformation of the bilayer beam, and can be controlled by a post-release heat-treat process, and the spatial geometrical patterning of the gold film on the polysilicon film. Not only is the range of travel increased to the entire initial gap of the vertical electrostatic actuator, but also the movement of the tip is controlled to yield a linear displacement - pull in step relationship by modifying the actuator topology (material distribution and geometry). We fabricated these actuators using the MUMPs surface micromachining process, and packaged them in-house. We measured full field deformed shapes of the actuator at each pull in step. The measurements compare well with the companion simulation results, both qualitatively and quantitatively.

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