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DYNAMIC PULL-IN AND SWITCHING FOR SUB-PULL-IN VOLTAGE ELECTROSTATIC ACTUATION

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Abstract: We propose and experimentally demonstrate a new MEMS switching technique using elastic potential energy to drive switching with electrostatic force used for switch control. This approach allows switching into pulled-in states at voltages significantly less than the quasi-static pull-in voltage. We have demonstrated switching into a pulled-in position using voltages much less than the pull-in voltage with a large torsional MEMS mirror, a high-speed torsional MEMS mirror, and a high-speed rectilinear MEMS switch that operates horizontally. Both high-speed devices have demonstrated switching in less than 500 ns over relatively large gaps.

Keywords: MEMS actuation, MEMS switching, micromirrors, high-speed switching, optical switching.

1. INTRODUCTION

We have developed a new MEMS switching technique that takes advantage of elastic potential energy in the mechanical structure in conjunction with the dynamic behavior of the structure to allow significant improvements in switching performance. Electrostatic forces are used for switch control. This approach allows lower actuation voltages, enables faster switching speeds, and requires less energy for switching.

We have used this technique to demonstrate switching into a pulled-in position using voltages much less than the pull-in voltage in a large torsional MEMS mirror, a high-speed torsional MEMS mirror, and a high-speed rectilinear MEMS switch that operates horizontally. The rectilinear device is a preliminary prototype for an integrated optical MEMS switch.

2. DYNAMIC SWITCHING

Dynamic switching operates between two opposing pulled-in positions defined by two fixed electrodes on either side of the moving electrode's unactuated equilibrium position. Fig. 1B shows a lumped parameter model operating according to this switching technique. Because the switch is always in one of two pulled-in states, the switch always possesses stored energy to drive switching.

Upon release from one pulled-in position the movable electrode will accelerate, overshoot its equilibrium position, and come near the second fixed electrode if the system is underdamped. Due to this close proximity, the second electrode can catch and hold the movable electrode in a pulled-in position with a voltage less than the pull-in voltage.

The hold voltage is the lower limit of the actuation voltage for the dynamic switching technique [1-3]; however, the actuation voltage may need to be higher if the mechanical resonance quality factor is too low. A quality factor as low as five can provide an appreciable decrease in the required actuation voltage.

The switch requires initialization (i.e. initial pull-in of the movable electrode from its undeflected equilibrium). This can be achieved by applying a voltage that exceeds the pull-in voltage; however, by again taking advantage of system dynamics this initial pull-in can also be achieved at a voltage much less than the pull-in voltage [2,3].

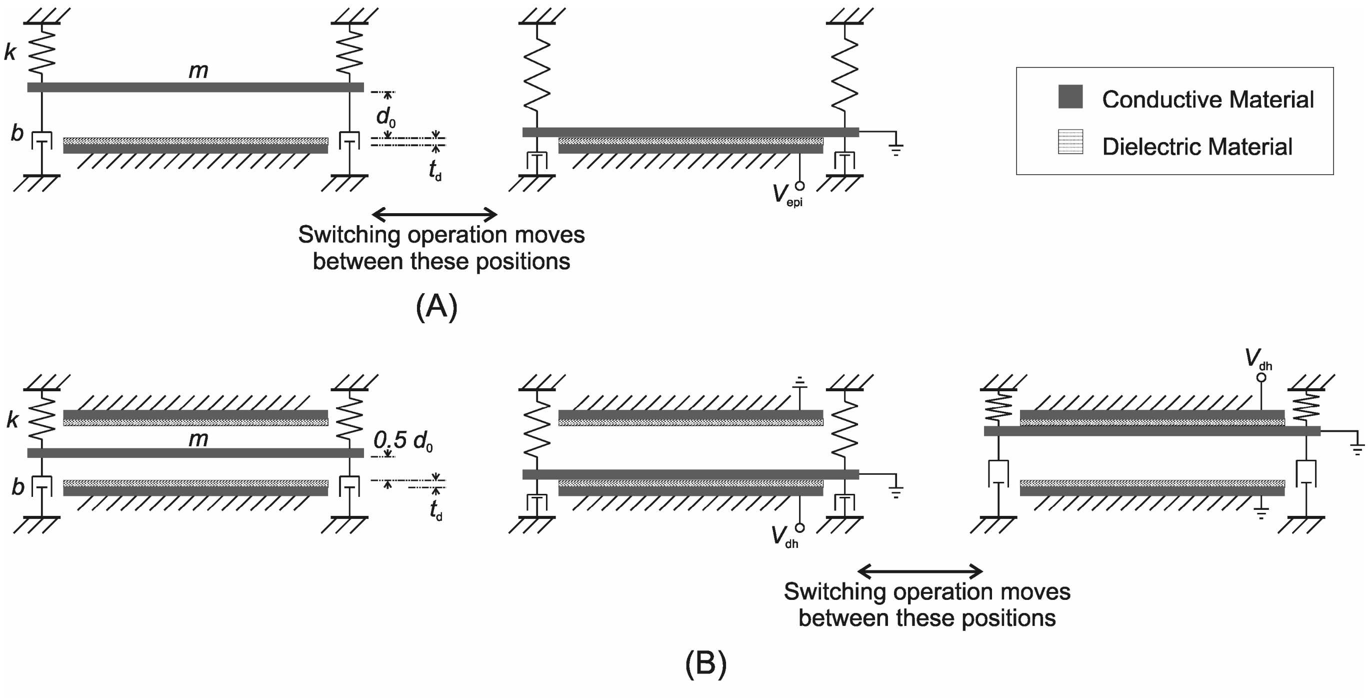

Fig. 1 Lumped parameter models of the electrode arrangement for (A) a standard parallel plate switch and (B) a dynamic MEMS switch. k is the mechanical stiffness, b is the mechanical damping, m is the mass of the moving electrode, V_{epi} is the minimum voltage to operate (A), and V_{dh} is the minimum voltage to operate (B).

2.1 Comparison with Electrostatic Actuation

Using the stored elastic potential energy and dynamic behavior of the structure to switch between states produces many benefits compared with standard MEMS switching techniques. Of the standard switching techniques, electrostatic actuation has been the most widely used and typically has the best general performance. Comparing the dynamic switching technique to standard electrostatic switching illustrates the benefits of dynamic switching.

Dynamic switching allows a combination of faster switching speeds, lower actuation voltage, and lower energy requirements. The reduction in required voltage results from two mechanisms. First, for a given displacement, the unactuated equilibrium position is half that of a standard electrostatic switch. This effect is taken advantage of in [4]. Second, the voltage required for the dynamic switching is limited by the hold voltage rather than the pull-in voltage.

To determine the decrease in voltage resulting from the dynamic switching technique for a comparable switch in terms of displacement and speed, we can evaluate the ratio of the required voltages for switches using the two switching techniques that have identical k, electrode overlap area, d_0, and m values. The ratio of the required voltage for the two switching techniques is

$$\frac{V_{dh}}{V_{epi}} = \sqrt{\frac{27 d_0 t_d^2}{8\left(t_d - \varepsilon_d d_0\right)^3}}, \qquad (1)$$

where ε_d is the relative permittivity of the dielectric isolation layer. Fig. 2 plots V_{dh}/V_{epi} for different values of t_d/d_0 with different dielectric materials (i.e. different ε_d) for Eq. (1). The dynamic switch always operates at a lower voltage than the standard electrostatic switch and, with optimized geometry, the voltage can be significantly lower.

It is important to realize that with a decrease in actuation voltage the dielectric isolation layer can also be reduced in thickness. Decreasing the dielectric layer thickness further decreases the voltage required for operation. This effect is in addition to the benefits predicted by Eq. (1).

Dynamic switching can also be used to increase switching speed while keeping the required voltage fixed. The switching speed of MEMS switches operated with standard

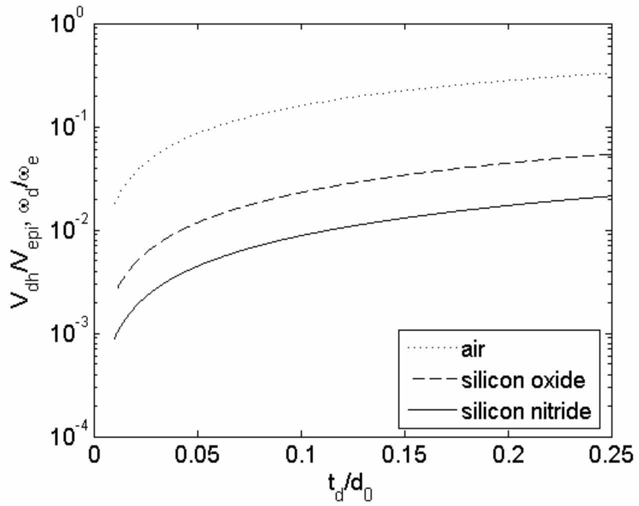

Figure 2: Voltage and speed of the dynamic switching technique compared with standard parallel plate switching for different dielectric layer thicknesses relative to the total switch displacement.

electrostatic actuation or dynamic actuation is tied to the resonant frequency of the mechanical structure. Therefore, comparing the resonant frequencies of these two switches provides a metric of the improvement in switching speed. Taking equal values for *m*, the electrostatic overlap area, d_0, and actuation voltage while varying *k* provides the mechanical resonant frequency ratio

$$\frac{\omega_e}{\omega_d} = \sqrt{\frac{27 d_0 t_d^2}{8\left(t_d - \varepsilon_d d_0\right)^3}}, \qquad (2)$$

where ω_e is the resonant frequency of the standard parallel plate electrostatic switch and ω_d is the resonant frequency of the dynamic switch. Note that this improvement in speed is identical to the improvement in actuation voltage in Eq. (1). The curves in Fig. 2, therefore, also illustrate the speed benefit for switches with equal actuation voltages.

Torsional dynamic switching has similar benefits relative to standard torsional electrostatic switching. While still significant, the benefits are reduced in a torsional arrangement due to the inability of torsional actuators to achieve isolation layers as thin as a parallel plate actuator.

3. EXPERIMENTAL RESULTS

We have experimentally demonstrated both dynamic switching between pulled-in states as well as pulling-in movable electrodes from their equilibrium positions at voltages much less than their pull-in voltages.

3.1 Large MEMS Mirror Switching Results

Fig. 3 is a SEM of a large torsional MEMS mirror. This device can displace ±10° and has mirror dimensions of 160 μm × 120 μm. This mirror was fabricated using Sandia National Laboratories SUMMiT V™ process.

Fig. 4 shows the results of the dynamic switching tests for the large torsional MEMS mirror. This test was conducted in air with a mechanical quality factor of approximately five. The device was tested by illuminating the mirror with a laser and recording the position of the reflected light with a position sensitive detector. We were able to achieve dynamic switching between pull-in states with an actuation voltage at 72% of the pull-in voltage with this device.

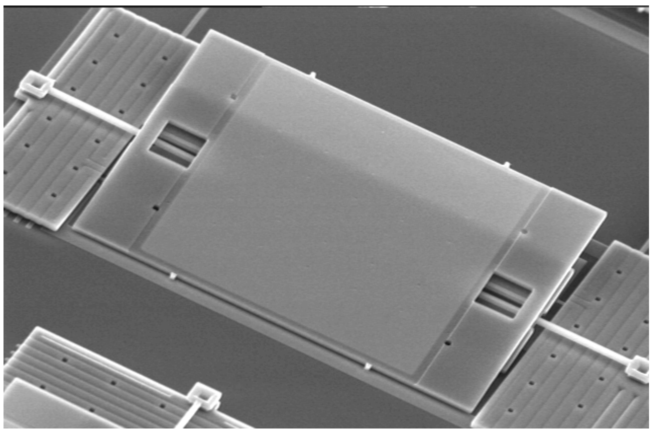

Fig. 3 SEM of the large MEMS mirror device. The mirror surface is 120 μm by 160 μm.

3.2 Horizontal Switch Results

Fig. 5 shows an optical micrograph of the horizontal switch device. This device is fabricated using a single 2.25 μm thick polysilicon layer on top of a silicon oxide isolation layer. The electrodes have a 50 nm silicon nitride layer coating for electrical isolation in the pulled-in state. The center electrode is fixed on both ends and is 140 μm long and 1.75 μm wide. This structure is ultimately intended to be combined with optical waveguides to create a high-speed integrated optical MEMS switch.

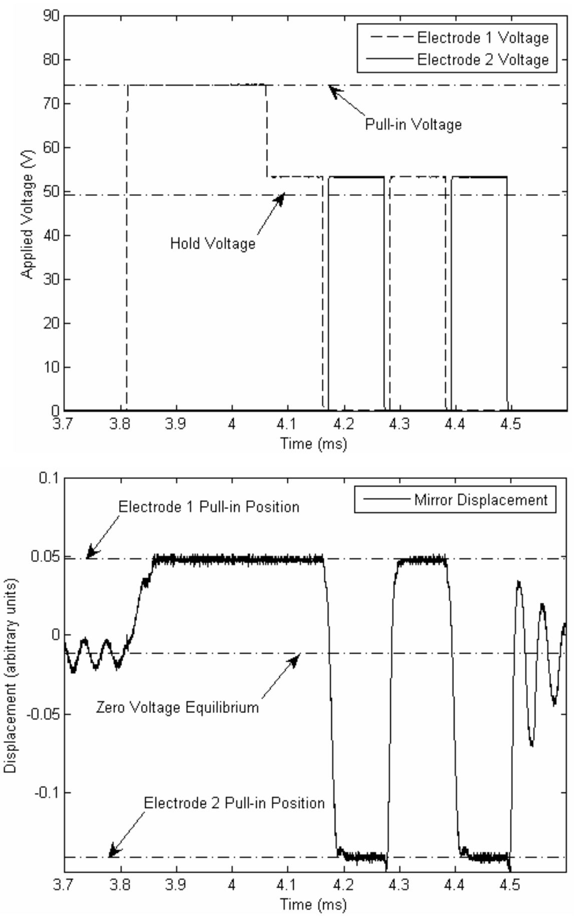

Fig. 4 Plots showing the applied voltage and the resulting dynamic switching of the large MEMS torsional mirror.

Fig. 6 shows the results of the dynamic switching tests. The device was tested in a vacuum chamber with laser light focused on the moving electrode by a long working distance objective lens through a window in the chamber. The objective lens collected the light reflected from the moving electrode. The intensity of the reflected light was measured by a photo detector. The intensity of reflected light changed with the electrode position.

After applying an initialization voltage that exceeded the pull-in voltage, the structure was switched back and forth between pulled-in states with voltages less than 75% of the pull-in voltage. The center electrode displaced 1.8 µm with a switching time between 350 to 500 ns.

3.3 Fast MEMS Mirror Switching Results

Fig. 7 shows a SEM image of a high-speed torsional mirror [5]. The device was fabricated in

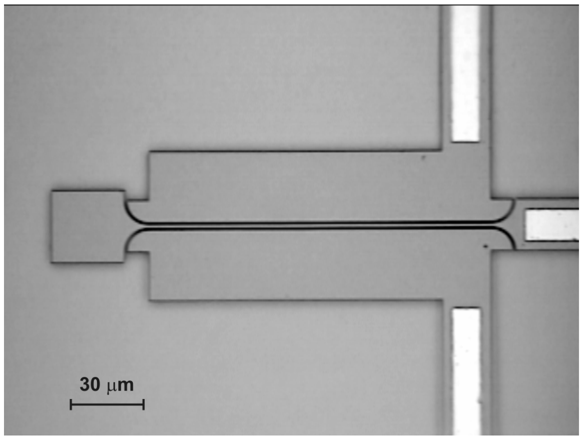

Fig. 5 Optical micrograph of the horizontal motion device.

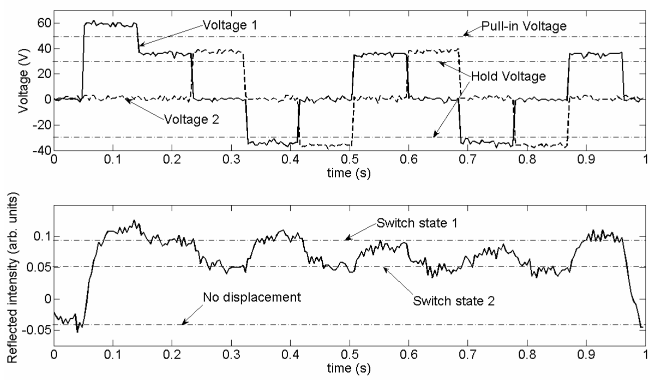

Fig. 6 Input voltage signals with the resulting reflected optical intensity from the horizontal motion device.

Sandia National Laboratories' SUMMiT V™ process. The mirror is 40 µm by 40 µm by 1.5 µm thick. The torsional springs on each side of the mirror are 1.0 µm thick by 3 µm long and 2 µm wide. The gap between the fixed electrodes and the torsional plate is 0.3 µm. The switch displacement is 0.6 µm.

For this device we used a closed loop oscillator circuit to achieve pull-in from the unactuated state with an actuation voltage 100 mV above the hold voltage using the resonant pull-in theory in [2]. The results are presented in Fig. 8. The required actuation voltage is less than 75% of the quasi-static pull-in voltage.

This device was also tested in a vacuum chamber. The readout was based on the change in capacitance of the structure. This device has a 750 kHz resonant frequency and has been switched between pulled-in states as fast as 225 ns at the pull-in voltage of the device [5].

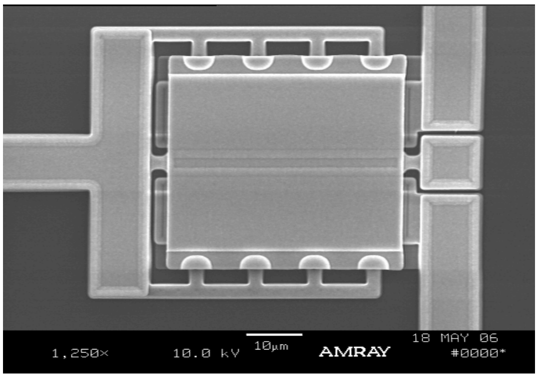

Fig. 7 SEM of the high-speed torsional MEMS mirror.

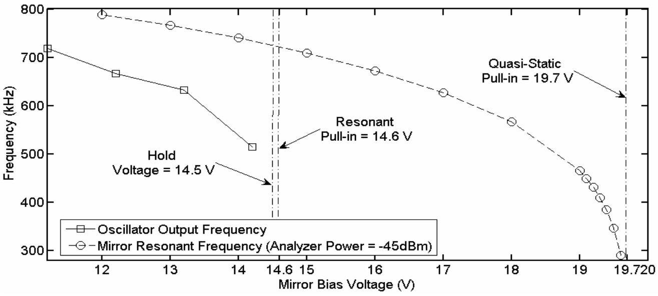

Fig. 8 Plot showing the effect of the bias voltage on the resonant frequency of the MEMS device and the non-resonant and resonant pull-in voltages. The resonant pull-in voltage is more than 25% less than the quasi-static pull-in voltage.

3.4 Discussion of Experimental Results

Each of these three devices experienced a decrease in the voltage required to achieve a pulled-in state in the range of 25 to 30%. The high-speed mirror and the horizontal switch structure both switched in less than 500 ns. While these results are an achievement, the theory discussed in section 2 predicts much more dramatic improvements are possible.

To achieve better results requires minimizing the hold voltage. The primary method available to reduce the hold voltage is to bring the electrodes into closer effective proximity in the pulled-in state. This can be done through either a smaller physical gap or by using a dielectric material with a larger relative permittivity.

4. CONCLUSION

Taking advantage of the energy stored in the mechanical structure of MEMS switches in conjunction with their dynamic behavior allows significant improvements in switching performance. These improvements include lower actuation voltage, faster switching speeds, and less energy required for switching. We have demonstrated the ability of these dynamic switching principles to allow better performance by achieving pulled-in positions with voltages less than the pull-in voltage with a variety of MEMS devices.

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